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A STUDY OF THE EFFECTS OF FULL THREE-PHASE REPRESENTATION IN POWER SYSTEM ANALYSIS

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A study of the effects of full three-phase

representation in power system analysis

by

Mahmood Seyed Mirheydar

A Dissertation Submitted to the

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I. INTRODUCTION

A. Introductory Background - Literature Review

Most analyses done in power systems use one-phase (1-ϕ) network representation. This assumes a balanced 3-ϕ network operated with balanced 3-ϕ generation and loads. In practice, a balanced network is obtained by transposition of transmission lines. This makes possible the treatment of many 3-ϕ network problems on a 1-ϕ basis with the use of symmetrical components [1,2,3].

In general, however, such an assumption is not always realistic. In practice, it is neither feasible to balance the load completely nor achieve perfectly balanced transmission impedances. Untransposed high voltage-lines and lines sharing the same right of way for considerable distances cause unbalances in the transmission line impedances.

As extra-high voltage lines increase and dominate the transmission network, the unbalanced effects of these untransposed lines have to be carefully analyzed. In this type of network, voltages and currents are unbalanced during normal operation [4,5]. Unbalanced loads that may exist in the system would contribute even more to these unbalances. If the unbalance is small, its effect on the overall network may be relatively unimportant, but its effect on components of the network may be serious. One example is the heating in synchronous machines resulting from negative sequence currents in the armature. Unbalanced 3-ϕ stator currents cause double-system-frequency currents to be induced in the rotor iron. These currents will quickly cause rotor overheating and serious damage if the generator is permitted to continue operating with such an unbalance [6]. Another example is the unpredictable current distribution which may cause incorrect protective relay operation. Hesse [7,8] has pointed out that I^2R losses due to zero-sequence circulating current in double-circuit lines could be high enough to justify line transposition. He also pointed to the importance of thoroughly investigating the influence of circulating currents on relay settings. Misoperation of ground overcurrent relays caused by zero-sequence currents have been reported in practice. Rusche and Bahl [9] reported the tripping of a 345-kV double-circuit line in Consumers Power Company transmission system at about 50% of the 2000 A circuit thermal rating. With such operating problems being common in the power system, it seems advisable to check the significance of unbalances whenever new untransposed EHV lines are added or whenever unbalanced loads are expected.

Transient or traveling wave phenomena play an important role in power system networks. They are caused by lighting discharges, switching operations and faults. Transient overvoltages arising from switching operations have been one of the controlling factors in the design of EHV air-insulated structures [10,11]. The improvements in EHV power circuit breakers have been carried out by many researchers over the years [12,13,14]. With these improvements, overvoltages caused by energization or re-energization of lines can now be made so low that the limiting factor determining how much the line insulation may be reduced might be determined by the overvoltage produced by single-line-to-ground fault [15,16]. Kimbark and Legate [15] concluded that a line-to-ground fault can produce an overvoltage on an unfaulted phase as high as 2.1 times normal line-to-ground crest voltage on a 3-ϕ line.

The transient overvoltage occurring in an unbalanced power system may not be the same as the overvoltage occurring in a balanced system. Ignoring the system unbalances in network transient analyses, therefore, could lead to an incorrect estimate of overvoltages and may result in a poor line insulation design.

B. Problem Formulation

The use of long-distance transmission and the presence of unbalanced loads motivated the development of analytical techniques for the assessment of power-system unbalance. Early techniques [7,8,17] were restricted to the case of isolated unbalanced lines operated from known terminal conditions. However, a realistic assessment of the unbalanced operation of an interconnected system, including the influence of any significant load unbalance, requires the use of 3-ϕ load-flow algorithms [5,18,19,20].

Literature search reveals that most work in this area to date has been mainly in development of programs rather than analysis of systems. To assess the impact of system unbalances it is necessary to study in detail the full 3-ϕ representation of the transmission network and the load. Based on these analyses, comparisons between balanced and unbalanced conditions may be conducted.

The effect of an untransposed transmission line on electromagnetic transients has been studied by many authors [10,21]. They all concluded that a completely untransposed line could be approximated by a continuously transposed line. The system used in these studies, however, consists of an isolated untransposed transmission line operated from known terminal conditions. In this case, the overall effect of network and loads as well as their possible unbalances are ignored. This, therefore, may not represent an actual situation. In order to investigate the effect of transmission system unbalances on the electromagnetic transients, it would be necessary to study the full 3-ϕ representation of the system. Currently, initial conditions obtained from balanced 3-ϕ networks are used in various network transient studies. The accuracy of using such initial condition assumptions should be evaluated to determine the significance of error that they may introduce in the solution.

For the steady state, the need for a full 3-ϕ load flow analysis depends primarily on the degree of system unbalances. These unbalances may or may not be significant. At any rate, the stage at which unbalances become significant is not known prior to the study. This would indicate that full 3-ϕ load flow analysis may not be necessary for all unbalanced systems. Furthermore, due to the iterative nature of 3-ϕ load flow programs, it would not be feasible to run such programs merely to obtain the degree of unbalances. Therefore, it would rather be appropriate to adopt an alternative non-iterative, quick, and easy-to-use method to give a good estimate of unbalances. Development of such a technique is one of the objectives of this dissertation.

C. Research Objectives

It is the intent of this dissertation to analyze and determine the impact of transmission system unbalances in power system analysis. The specific objectives of this research may be summarized as follows:

1. Determination of the effects of untransposed transmission lines and unbalanced loads on the steady-state load flow analysis.
2. Determination of the effects of untransposed transmission lines and unbalanced loads on the transient overvoltages due to fault surges.
3. Development of a non-iterative system reduction technique as an alternative to the three-phase load flow program to be used in unbalanced steady-state analysis.

This study will enable a utility to decide when a full three-phase representation is required in power system analysis.

D. Research Outline

The purpose of this work is to investigate the effects of untransposed transmission lines and unbalanced loads on the accuracy of the 3-ϕ balanced representation that is normally used in power system analysis. The steady-state analysis is focused on the errors that are introduced by the utilization of this balanced representation. These errors in turn may introduce errors in the transient analysis. Therefore, the behavior of the system in the transient state due to these errors also will be investigated.

This work is divided into six chapters and two appendices. Whereas the first chapter deals with an introduction and formulation of the problem, the second chapter is devoted to the analysis of 3-ϕ unbalanced systems in the steady state. Sensitivity of unbalances to the length of untransposed lines and to system loading conditions is analyzed, and the power coupling phenomena that exist in unbalanced systems are discussed. In addition, a non-iterative system reduction method to estimate the degree of system unbalances is presented.

Chapter III presents some numerical results using the 3-ϕ load-flow program (described in Appendix I) to illustrate the effects of system unbalances under various steady-state unbalanced conditions. Furthermore, this chapter shows the effect of changes in the length of untransposed lines and system loading on unbalances and also the effect of the power coupling phenomena. Finally, the application and compatibility of the newly developed system reduction method are discussed and some numerical examples are given.

Chapter IV deals with the analysis of the impact of unbalanced load and untransposed lines on electromagnetic transients.

Chapter V includes results of the transient analyses using the Electromagnetic Transient Program (EMTP). This program is described in Appendix I. The effects of untransposed transmission lines and unbalanced loads on transient overvoltages due to fault clearing is presented and the accuracy of using balanced initial conditions in network transient analysis is evaluated.

The last chapter, devoted to conclusions, discusses the principal contributions of this dissertation.

II. STEADY-STATE THREE-PHASE UNBALANCE ANALYSIS

A. Introduction

Under normal conditions, electrical transmission systems operate in their steady-state mode and the basic calculation required to determine the characteristics of this state is termed the load flow (or power flow).

Load flow is the study conducted to determine the steady operating conditions in a system and is the most frequently carried out study by a utility. Much work has been done in this area, and multitudes of computer programs have been written to solve such a problem. Most past approaches were for balanced 3-ϕ network operated with balanced 3-ϕ generation and loads. A balanced 3-ϕ network is assumed so that the transmission network is represented by its positive sequence network. The elements of the network are therefore not mutually coupled; 3-ϕ loads are assumed to be completely balanced, and 1-ϕ loads can be treated as sustained 1-ϕ faults (in short circuit studies).

In studies when more detailed steady-state analysis of a power system is desired, the system should be represented as a full 3-ϕ network. Mutual couplings between parallel transmission lines and load unbalances should be considered in the analysis. Steady-state solution of the 3-ϕ unbalanced system may be obtained from 3-ϕ load-flow programs.

The assumption of balanced 3-ϕ representation being unrealistic and problems associated with unbalances are well described in Chapter I.

Every unbalanced element, be it an untransposed line or an unbalanced load, if added to the system, would contribute some unbalances to the system. This newly added unbalance may have an addition or a cancellation effect which cannot be readily known. In other words, by merely knowing the unbalance degree of the element, one cannot estimate its effect on the system simply by inspection. Therefore, to determine the effect of unbalances, the 3-ϕ representation of the system as a whole should be considered in the analysis. It would be rather interesting, however, to find a correlation between the unbalances and changes in the system, namely, changes in the transmission network and system loading.

In this chapter, the sensitivity of network unbalances to the system parameters, namely, the length of untransposed lines and system loading will be analyzed, unbalances due to unbalanced load will be studied, and the power coupling phenomena that exist in unbalanced systems will be discussed.

In addition, a non-iterative method to estimate the degree of system unbalances will be introduced that can be used as an alternative to 3-ϕ load-flow programs.

Unless otherwise specified, matrix notations in the symmmetrical components frame of reference will be used throughout this dissertation to represent the system elements, voltages, and currents.

B. Effects of Three-Phase Transmission System Unbalance

The primary concern about system unbalances in this study is their possible effects on system components and the relays protecting these components. A review of protection schemes and their criteria is necessary to investigate the effects of system unbalances. The components of interest are: generators, power transformers, and transmission lines.

1. Protection of generators against negative sequence currents

Extensive studies have shown that, in the majority of cases, the negative sequence current relay will properly coordinate with other system-relaying equipment [22,23].

The fact that the system-relaying equipment will generally operate first might lead to the conclusion that, with modern protective equipments, protection against unbalanced 3-ϕ currents during short circuits is not required [24,25]. This conclusion might be reached also from the fact that there has been no great demand for improvement of the existing forms of protection [6]. Back-up relaying, however, is mainly set to operate for short-circuit currents and not for current unbalances which are caused by system unbalances; as a result, back-up relaying will not operate for these types of imbalance.

Standards have been established for operation of generators with unbalanced stator current [26,27]. The criteria imposed on generators' continuous current unbalance used in this study are 5% or 10% of rated stator current depending on the type and rating of the machine.

It can be shown that the generator rated current I_G in per unit Ampere (puA) is

$$I_G=(MVA_G/BMVA)(KVB/KVG)$$

where

MVA_G = generator rated MVA

BMVA = system base MVA

KVB = system base voltage, kV line-to-line

KVG = generator rated voltage, kV line-to-line

therefore, the maximum allowable negative sequence current induced in the generator in puA for a system base of 100 MVA would be

$$I_2 = (.05/100)(KVB/KVG)MVA_G \quad \text{puA for 5\% limitation} \qquad (2.1)$$

or

$$I_2 = (.10/100)(KVB/KVG)MVA_G \quad \text{puA for 10\% limitation} \qquad (2.2)$$

Equations (2.1) and (2.2) for different values of MVA_G are plotted in Figure 1. Thus, knowing the generator type and its ratings, the criteria imposed on the negative sequence current in puA can be obtained from Figure 1.

2. Power transformer protection schemes

Power transformers and power autotransformers are protected against short-circuits by percentage differential relays that must satisfy the following basic requirements [6,28]:

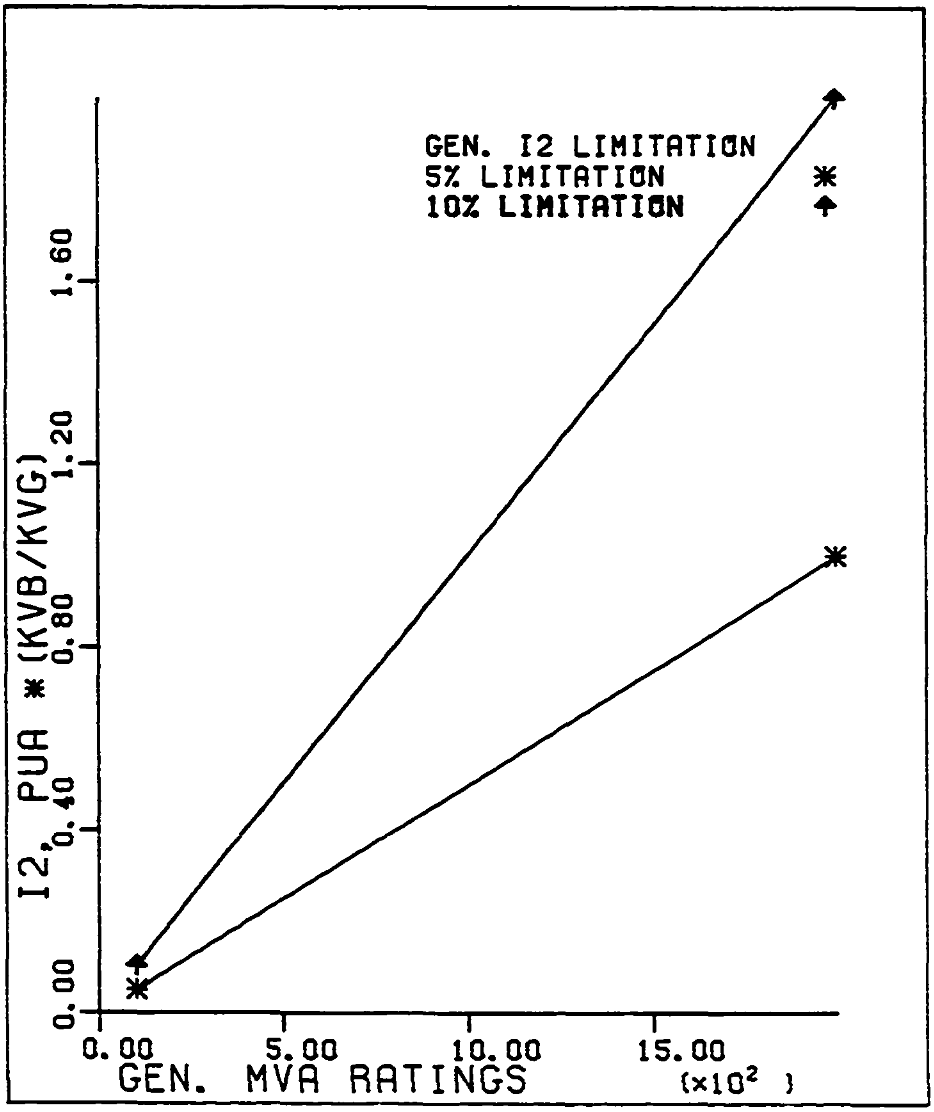

FIGURE 1. Relation between generator MVA ratings and maximum allowable negative-sequence current

1. The differential relay must not operate for load or external faults.
2. The relay must operate for severe enough internal faults.

Current transformers (CT) on the wye side is connected in delta to prevent zero sequence current (I_0) from flowing in the relay operating coil which would otherwise cause the relay to operate undesirably for external ground faults. A delta CT connection circulates the I_0 inside the delta and therefore keeps it out of the external connections to the relay. This, of course, does not mean that the differential relay cannot operate for a single-line to ground (SLG) fault in the transformer; the relay will not receive I_0 but it will receive and operate on the positive and negative sequence components of the fault current (I_1 and I_2). CT's are sometimes connected in wye on the wye side of the transformer and in delta on the delta side, but this is done under the condition that a zero-sequence-current shunt is used, which keeps the I_0 out of external secondary of wye-connected CT's [6,28].

I_0, due to system unbalances, therefore, cannot be detected by the transformer differential relay, mainly because the I_1 and I_2 components of the unbalanced current are well below the magnitude of the short-circuit I_1 and I_2. As a result, unbalanced currents, due to system unbalances alone, cannot be detected by the transformer differential relays, and relay misoperation should not be of concern. However, a differentially protected transformer bank should have inverse-time overcurrent relays, preferably energized from CT's other than those associated with differential relays, to trip fault-side breakers when external faults persist for too long a time [6]. Therefore, an unbalance analysis may be required, in this case, to determine the degree of unbalanced currents to ensure normal operation of the back-up overcurrent relays.

No standards currently exist for the transformer continuous unbalance requirements.

3. Transmission line protection against ground currents

In transmission line relaying applications, transmission system unbalances normally are ignored and relaying criteria are mainly based on the results of a short-circuit study. Among ground relays, the two most common in practice are: the ground overcurrent relay and the ground distance relay.

a. Ground overcurrent relays Overcurrent relays, in general, achieve selectivity on the basis of current magnitude. A minimum setting of about 200 A is normally selected, mainly because system unbalances are ignored. In this case, relay misoperation due to excessive ground current (I_0) is likely and unbalance analysis, therefore, is required to ensure normal operation of relays.

b. Ground distance relays Distance relays achieve selectivity on the basis of impedance rather than current magnitude. Relays do not operate unless the impedance seen by the relay is reduced significantly, and this can happen only during short circuits. In other words, I_0 due to system unbalances cannot force the relay to operate; therefore, for this type of protection, unbalance analysis will not be necessary.

A current magnitude of 1.0 puA (167.0 A in a 345 kV system) is used in this study as a criteria limit on the zero-sequence component of the unbalanced line currents.

C. Sensitivity of Network Unbalances to the Length of Untransposed Transmission Line and the System Loading

To obtain a relation between the network unbalances and the length of untransposed lines, a simple two-bus system shown in Figure 2 is considered.

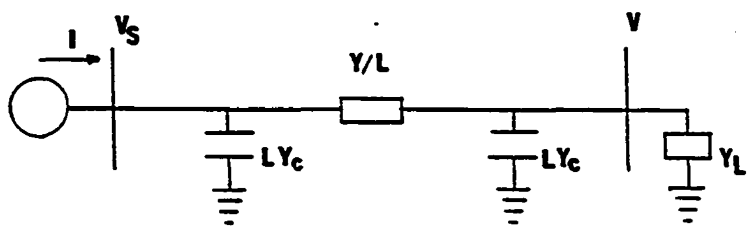

FIGURE 2. Two-bus system

This system consists of a source, a transmission line, and a load represented by constant admittances to ground. The only unbalanced element in this case is the line which is represented untransposed.

The following symmetrical component variables are used:

I = current at the sending end of the line, puA

Y = line series admittance matrix, (half of the total shunt admittance) puMhos-mile

Y_c = line shunt admittance matrix, puMhos/mile

Y_L = equivalent admittance matrix of the load, puMhos

V_s, V = voltages at the sending end and the receiving end of the line, respectively, per unit Volt (puV)

L = length of the line, mile

The current at the sending end of the line is

$$I = LY_cV_s + (Y/L)(V_s-V) \tag{2.3}$$

and the voltage at the receiving end is

$$V = (LY_c + Y_L + Y/L)^{-1}(Y/L)V_s \tag{2.4}$$

Substituting (2.4) in (2.3) yields

$$I = (LY_c + Y/L)V_s - (Y/L)(LY_c + Y_L + Y/L)^{-1}(Y/L)V_s \tag{2.5}$$

The dependence of I on L can best be described by writing

$$I = LY_c\,V_s + LY_c\,V + Y_LV \tag{2.6}$$

Although V as shown in (2.4) depends on many parameters, considering the no load case (Y_L=0), (2.4) would become

$$V = (LY_c + Y/L)^{-1}(Y/L)V_s \tag{2.7}$$

and since Y usually dominates Y_c, (2.7) can be approximated by

$$V \approx V_s$$

and (2.6) becomes

$$I \approx 2LY_cV_s \tag{2.8}$$

An equation of type (2.8) does not include the equivalent load admittances but it clearly shows that the sequence components of the line current (I_0 and I_2) increase as line length increases. Returning to (2.5), using typical 345 kV line parameter and assuming

$$V_s = \begin{bmatrix} 0.0 \\ 1.0\underline{/0.0} \\ 0.0 \end{bmatrix} \text{ puV}$$

with a 3-ϕ load of 90+j60 MVA, the relationship between I_0 or I_2 and various lengths of the line is obtained and is shown in Figure 3. This example was provided here, mainly, to show that unbalances increase with the length of the untransposed line even when the load is not neglected. This could not have been readily shown by inspecting equation (2.5).

To find a correlation between the system loading and unbalances, the two-bus system shown in Figure 2 is considered except, in this case, system loading rather than the length of the transmission line is varying.

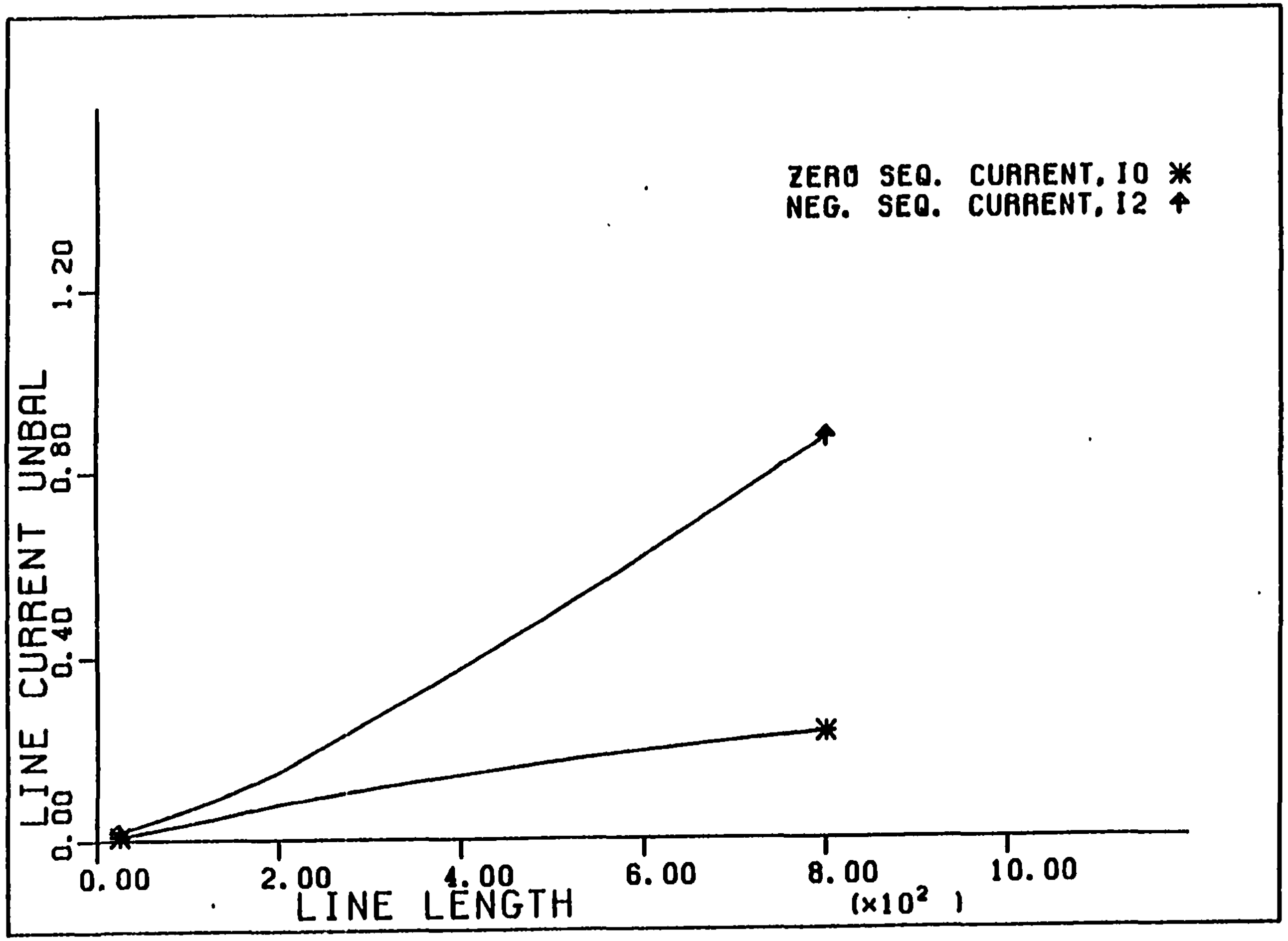

FIGURE 3. Relation between zero-sequence and negative-sequence components of unbalanced current with the length of untransposed transmission line

Equation (2.5) gives a relation between the current I and the equivalent load admittances with L maintained constant. The first part of (2.5) therefore remains constant whereas the second part depends on Y_L and decreases as load increases since Y_L increases. That is, with the first part being constant, each time the load increases, a smaller quantity will be subtracted from the first part and, as a result, the current I will increase.

Using the same line parameters chosen earlier, with L=50 miles, the relationship between I_0 or I_2 and various loadings is determined and is shown in Figure 4. It must be pointed out here that the power factor of the loads considered in this case is not the same as the load power factor in the previous case; therefore, one should not anticipate any correlation between and 4.

It is clear from Figures 3 and 4, however, that unbalances are sensitive to changes in both the length of the untransposed line and in the system loading. The way that unbalances change and how much they change depends on network configuration and system loading. For a fixed network configuration, it appears from these analyses that the maximum degree of unbalance would exist when system loading is maximum.

In the literature, it is common to refer to current unbalances with unbalance factors. Caution should be warranted when using these factors.

Current unbalance factors, by definition, are the ratio of the zero-sequence and negative-sequence components of the unbalanced current

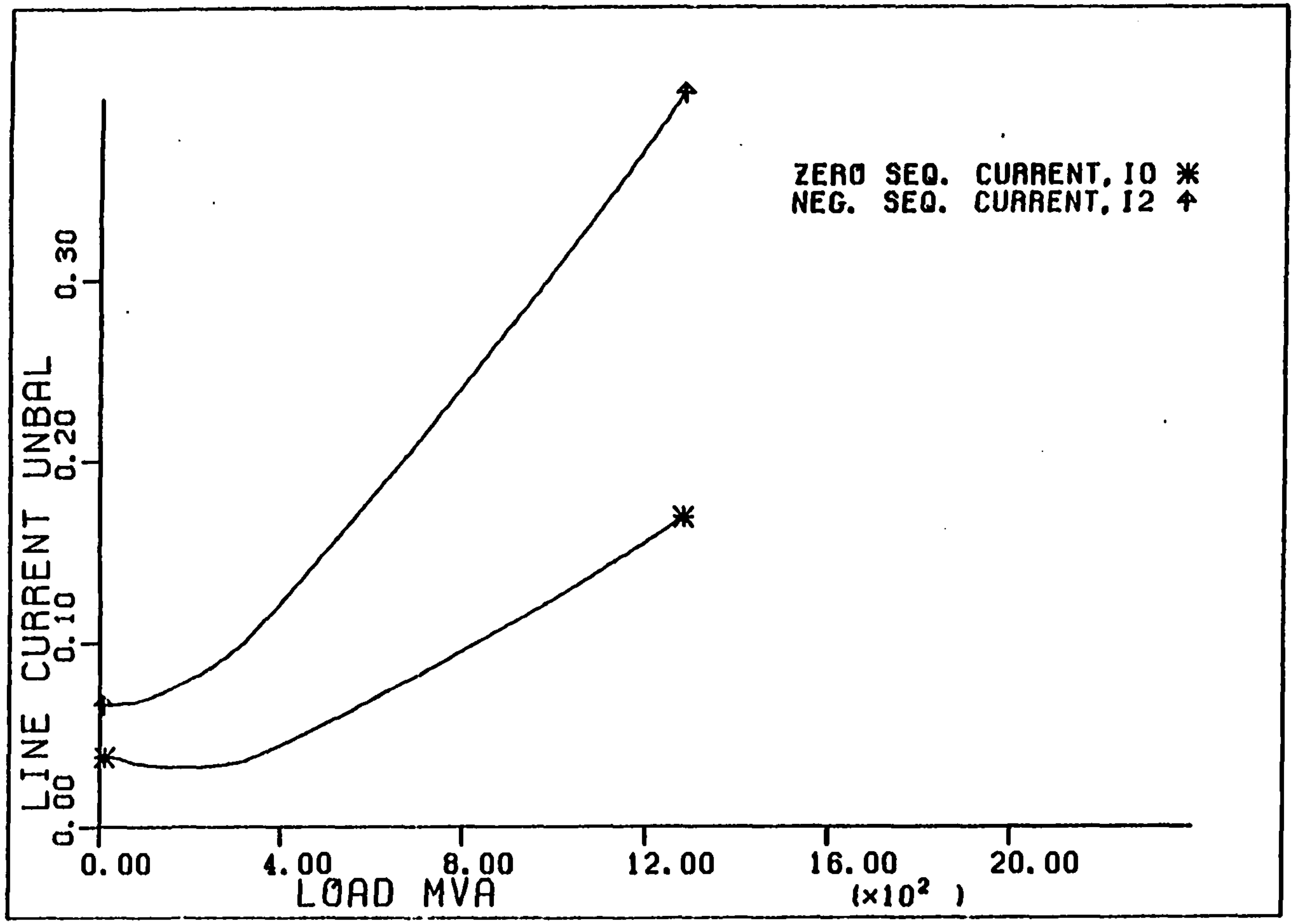

FIGURE 4. Relation between zero-sequence and negative-sequence components of unbalanced current with system loading

to the positive-sequence component of the current. In cases, when the positive-sequence current is very low (e.g., lightly loaded line), the unbalanced factors are relatively high. However, as the positive-sequence current increases (as load increases), the factors will tend to decrease to relatively constant values. This is because zero-sequence and negative-sequence currents do not increase as rapidly as the positive sequence current. To demonstrate this, the percent zero-sequence and negative-sequence unbalance factors of the unbalanced current used in obtaining the Figure 4 are determined and are shown in Figure 5. It is clear from this figure that current unbalance factors obtained at light loads (low positive-sequence current) are much bigger than those determined at higher loading. Thus, it would be more meaningful to refer to these factors when the current is near its rated value. At any rate, to avoid misusing of the current unbalance factors, it would be best if one referred to I_0 and I_2 in puA rather than in percentage of the positive-sequence current.

D. Analyses of Unbalanced Loads

It is rather obvious that unbalanced loads contribute some unbalances to the system. These unbalances vary in magnitude from insignificant to very significant depending on how unbalanced the load might be.

In this section, unbalances due to unbalanced 3-ϕ loads and 1-ϕ loads, based on some assumptions, are analyzed and discussed.

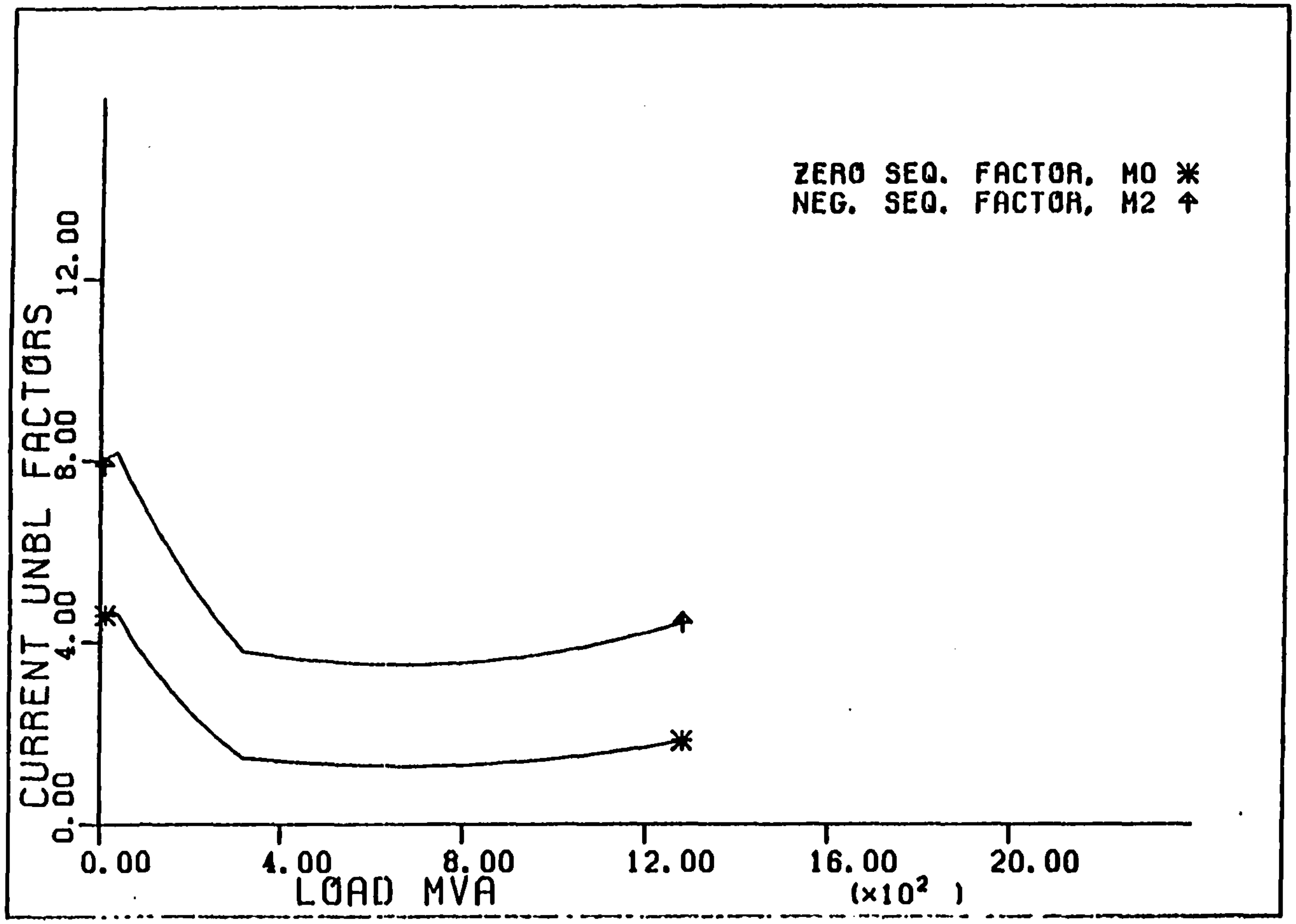

FIGURE 5. Relation between zero-sequence and negative-sequence unbalance factors with system loading

Consider an isolated 3-ϕ load with following real and reactive powers (P's and Q's):

$P_a = P + s_1$

$P_b = P + s_2$

$P_c = P + s_3$

$Q_a = Q + t_1$

$Q_b = Q + t_2$

$Q_c = Q + t_3$

where

P,Q = average active and reactive power per phase in MW and MVAR, respectively

P_i, Q_i = actual active and reactive power per phase in MW and MVAR, respectively, i=a,b,c

s_i, t_i = degree of load power unbalance in MW and MVAR, respectively, i=1,2,3

Let us assume that

$$s_1 + s_2 + s_3 = 0 \qquad (2.9)$$

$$t_1 + t_2 + t_3 = 0 \qquad (2.10)$$

In other words, it is assumed that the total 3-ϕ power is constant and is equal to the total 3-ϕ power of the load as if it were balanced. As a result of this assumption, P and Q can be written as

$P = (P_a + P_b + P_c)/3$

$Q = (Q_a + Q_b + Q_c)/3$

In addition, it is assumed that

$$|V_a| = |V_b| = |V_c| = V$$

where

$|V_i|$ = phase i voltage at the load in puV, i=a,b,c

The equivalent load admittances to ground are

$$Y_i = (1/V^2)(3P_i/BMVA - j3Q_i/BMVA) \text{ pu}, \quad i=a,b,c$$

where

BMVA = 3-ϕ base MVA

The equivalent load admittance matrix in a,b,c frame of reference is then

$$Y_{a,b,c} = (3/V^2 BMVA) \begin{bmatrix} P+s_1-jQ-jt_1 & 0 & 0 \\ 0 & P+s_2-jQ-jt_2 & 0 \\ 0 & 0 & P+s_3-jQ-jt_3 \end{bmatrix}$$

Using the similarity transformation , the equivalent load admittance matrix in the symmetrical components frame of reference can be written as

$$Y_{0,1,2} = A^{-1} Y_{a,b,c} A$$

which gives

$$Y_{0,1,2} = (1/V^2 BMVA) \begin{bmatrix} Y_S & Y_{M1} & Y_{M2} \\ Y_{M2} & Y_S & Y_{M1} \\ Y_{M1} & Y_{M2} & Y_S \end{bmatrix}$$

where

$$Y_S = 3P - 3Q$$

$$Y_{M1} = s_1 + a^2 s_2 + as_3 - j(t_1 + a^2 t_2 + at_3)$$

$$Y_{M2} = s_1 + as_2 + a^2 s_3 - j(t_1 + at_2 + a^2 t_3)$$

Now, by applying a balanced voltage across the load

$$V_{0,1,2} = \begin{bmatrix} 0.0 \\ 1.0\underline{/0.0} \\ 0.0 \end{bmatrix} \quad \text{puV}$$

the sequence currents in the load from

$$I_{0,1,2} = Y_{0,1,2} \, V_{0,1,2}$$

would be

$$I_0 = Y_{M1}/\text{BMVA} \qquad \text{puA} \tag{2.11}$$

$$I_2 = Y_{M2}/\text{BMVA} \qquad \text{puA} \tag{2.12}$$

The sequence currents given by (2.11) and (2.12) would, then, approximate the maximum possible unbalance that is caused by the load.

Using the criteria imposed on the sequence currents (given in section A), (2.11) and (2.12) can be written as

$$I_0 = Y_{M1}/\text{BMVA} < 1.0 \qquad \text{puA} \tag{2.13}$$

$$I_2 = Y_{M2}/\text{BMVA} < (.05 \text{ or } .10)I_{GS} \qquad \text{puA} \tag{2.14}$$

where

I_{GS} = rated current of the smallest generator in the system

An unbalanced load with I_0 and I_2 close to the limits given in (2.13) and (2.14) would require an unbalance analysis to ensure a safe and normal operation of the system. In a system with only one unbalanced load with insignificant degree of unbalances (obtained from (2.13) and (2.14)), unbalance analysis of the system may not be necessary. However, a combination of such unbalanced loads would require an unbalance analysis, since the unbalances due to each individual load may add and exceed the criteria limits.

For a 1-ϕ load on phase a

$$P_b = P_c = Q_b = Q_c = 0$$

In order for (2.9) and (2.10) to hold, s's and t's can be written as

$$s_1 = 2P$$
$$s_2 = -P$$
$$s_3 = -P$$
$$t_1 = 2Q$$
$$t_2 = -Q$$
$$t_3 = -Q$$

Y_{M1} and Y_{M2} would then become

$$Y_{M1} = Y_{M2} = 3P - j3Q \quad \text{MVA}$$

or

$$I_0 = I_2 = (3P - j3Q)/\text{BMVA} \quad \text{puA} \tag{2.15}$$

with s's and t's given in above, phase a power would be

$P_a = 3P$

$Q_a = 3Q$

and (2.15) can be written as

$$I_0 = I_2 = (P_a - jQ_a)/BMVA \quad puA \tag{2.16}$$

For 1-ϕ load on phase b, (2.16) becomes

$$I_0 = I_2 = a^2(P_a - jQ_a)/BMVA \quad puA \tag{2.17}$$

and for the 1-ϕ load on phase c

$$I_0 = I_2 = a(P_a - jQ_a)/BMVA \quad puA \tag{2.18}$$

(2.16)-(2.18) are all equal in magnitude, and can be written as

$$|I_0| = |I_2| = (P_{1\phi}{}^2 + Q_{1\phi}{}^2)^{\frac{1}{2}}/BMVA \quad puA \tag{2.19}$$

where

$P_{1\phi}$ and $Q_{1\phi}$ are single-phase P and Q in MW and MVAR, respectively.

The sequence currents given by (2.19) represent the maximum possible imbalance that could be caused by a 1-ϕ load.

Using the criteria imposed on I_0 and I_2, (2.19) can be written as

$$(P_{1\phi}{}^2 + Q_{1\phi}{}^2)^{\frac{1}{2}}/BMVA < 1.0 \quad puA \tag{2.20}$$

or

$$(P_{1\phi}{}^2 + Q_{1\phi}{}^2)^{\frac{1}{2}}/BMVA < (.05 \text{ or } .10)I_{GS} \quad puA \tag{2.21}$$

Both conditions given in (2.20) and (2.21) must hold in order for the criteria to be satisfied. It should be mentioned that (2.19) is derived based on the assumption that the variations in the magnitude of phase voltages at the load are not significant. A large 1-ϕ load with relatively low power factor will cause a significant change in the magnitude of phase voltages, and therefore, the sequence currents obtained by (2.19) would not represent a very good estimate.

At any rate, the purpose of (2.13), (2.14), (2.20), and (2.21) are merely to estimate the possible degree of unbalances that could be caused by unbalanced loads to justify a 3-ϕ analysis of the system.

Caution should be warranted when a combination of unbalanced loads exist in the system. As was mentioned earlier, due to the principle of superposition, unbalances may add and exceed the criteria limits. In such cases, 3-ϕ analysis of the system may be justifiable.

E. Power Coupling Phenomena

An interesting problem has surfaced during this study. It was noted in many instances that the receiving end power in some phases of transmission lines in the system are somewhat higher than the sending end power, which would indicate that the power loss on that phase is negative. This is because some external powers are generated by the induced EMF's due to the mutual coupling effects between the phases of the line. These external powers are unbalanced when the induced voltage is unbalanced, thus causing some increase in the power at the receiving end of the line.

This can best be described by means of equations. For this purpose, consider an isolated 3-ϕ transmission line shown in Figure 6.

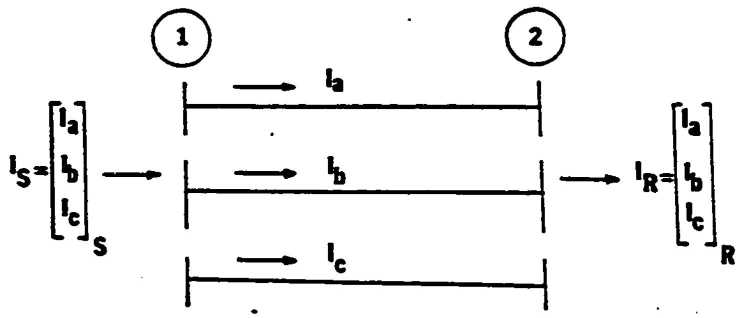

FIGURE 6. An isolated 3-ϕ transmission line

To simplify the equations, the effects of line chargings will be neglected. Let

ΔV_p = voltage drop in phase p

I_p = phase p current

$S_{Sp} = P_{Sp} + jQ_{Sp}$ = total power at the sending end of phase p

$S_{Rp} = P_{Rp} + jQ_{Rp}$ = total power at the receiving end of phase p

$S_{Lp} = P_{Lp} + jQ_{Lp}$ = total power loss in phase p

Z_{pp} = self series impedance of phase p

$Z_{pq} = Z_{qp}$ = mutual series impedance between phases p and q

$p,q = a,b,c$

The voltage drop in each phase of the line may be written as

$$\Delta V_a = Z_{aa}I_a + Z_{ab}I_b + Z_{ac}I_c$$
$$\Delta V_b = Z_{ab}I_a + Z_{bb}I_b + Z_{bc}I_c$$
$$\Delta V_c = Z_{ac}I_a + Z_{bc}I_b + Z_{cc}I_c$$

The total power loss in each phase is then

$$S_{La} = \Delta V_a I_a^* = Z_{aa}|I_a|^2 + (Z_{ab}I_b + Z_{ac}I_c)I_a^* \tag{2.22}$$
$$S_{Lb} = \Delta V_b I_b^* = Z_{bb}|I_b|^2 + (Z_{ab}I_a + Z_{bc}I_c)I_b^* \tag{2.23}$$
$$S_{Lc} = \Delta V_c I_c^* = Z_{cc}|I_c|^2 + (Z_{ac}I_a + Z_{bc}I_b)I_c^* \tag{2.24}$$

(2.22)-(2.24) indicate that the power loss in each phase consists of a self term and a mutual term contributed from the other phases. The total power at the receiving end may be written as

$$P_{Rp} + jQ_{Rp} = P_{Sp} + jQ_{Sp} - (P_{Lp} + jQ_{Lp}) \tag{2.25}$$

Due to this phenomena, either P_{Lp}, Q_{Lp} or both could be negative. In this case, as is shown by (2.25), the receiving end power would become larger than the sending end power.

The total 3-ϕ power loss, however, is positive (both P and Q), whether or not the power loss in one or two of the phases is negative. This may be shown as follows:

Total 3-ϕ loss can be written as

$$S_L|_{3\phi} = \Delta V_a I_a^* + \Delta V_b I_b^* + \Delta V_c I_c^* \tag{2.26}$$

Substituting (2.22)-(2.24) in (2.26) would yield

$$S_L|_{3\phi} = Z_{aa}|I_a|^2 + Z_{bb}|I_b|^2 + Z_{cc}|I_c|^2$$
$$+ Z_{ab}I_bI_a^* + Z_{ab}I_aI_b^* + Z_{ac}I_cI_a^*$$
$$+ Z_{ac}I_aI_c^* + Z_{bc}I_cI_b^* + Z_{bc}I_bI_c^* \quad (2.27)$$

Assuming

$$I_a = |I_a|/\underline{\alpha}$$
$$I_b = |I_b|/\underline{\beta}$$
$$I_c = |I_c|/\underline{\gamma}$$

then

$$I_aI_b^* = |I_a|\ |I_b|/\underline{\alpha - \beta}$$
$$I_bI_a^* = |I_a|\ |I_b|/\underline{\beta - \alpha}$$

From the phasor diagram shown in Figure 7, the following identities can be derived,

$$I_aI_b^* + I_bI_a^* = 2|I_a||I_b|\cos\ (\alpha - \beta) \quad (2.28)$$

Similarly,

$$I_aI_c^* + I_cI_a^* = 2|I_a||I_c|\cos\ (\alpha - \gamma) \quad (2.29)$$
$$I_bI_c^* + I_cI_b^* = 2|I_b||I_c|\cos\ (\beta - \gamma) \quad (2.30)$$

Substituting (2.28)-(2.30) in (2.27) gives

$$S_L|_{3\phi} = Z_{aa}|I_a|^2 + Z_{bb}|I_b|^2 + Z_{cc}|I_c|^2$$
$$+ 2Z_{ab}|I_a||I_b|\cos\ (\alpha - \beta) + 2Z_{ac}|I_a||I_c|\cos\ (\alpha - \gamma)$$
$$+ 2Z_{bc}|I_c||I_b|\cos\ (\beta - \gamma) \quad (2.31)$$

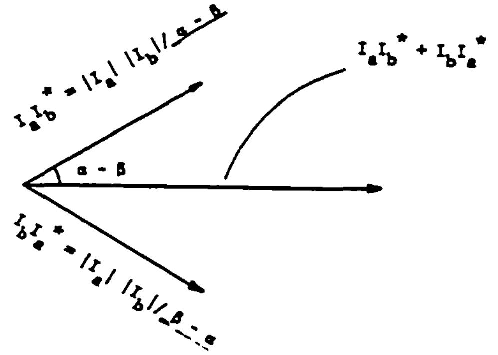

FIGURE 7. Phasor diagram to obtain the identity given in (2.28)

Now, let us assume an extreme case of

$\alpha - \beta = 180°$

and

$\alpha - \gamma = 180°$

then

$\beta - \gamma = 0$

and (2.31) becomes

$$\begin{aligned} S_L|_{3\phi} &= Z_{aa}|I_a|^2 + Z_{bb}|I_b|^2 + Z_{cc}|I_c|^2 \\ &\quad - 2Z_{ab}|I_a||I_b - 2Z_{ac}|I_a||I_c \\ &\quad + 2Z_{bc}|I_c||I_b \end{aligned} \tag{2.32}$$

(2.32) is positive if the following condition holds

$$Z_{aa}|I_a|^2 + Z_{bb}|I_b|^2 + Z_{cc}|I_c|^2 + 2Z_{bc}|I_c||I_b >$$
$$2(Z_{ab}|I_a||I_b + Z_{ac}|I_a||I_c)$$

which normally is true. This indicates that the 3-ϕ active and reactive power losses are positive.

Now, as a special case, assume that this line and every other element in the system are balanced. Then, the following are true:

$$Z_{pp} = Z_S$$
$$Z_{pq} = Z_M$$
$$I_a + I_b + I_c = 0$$
$$|I_a| = |I_b| = |I_c| = I$$
$$p,q = a,b,c$$

(2.22) can then be written as

$$S_{La} = (Z_S - Z_M)|I|^2 \tag{2.33}$$

Similarly, (2.23) and (2.24) would become

$$S_{Lb} = (Z_S - Z_M)|I|^2 \tag{2.34}$$
$$S_{Lc} = (Z_S - Z_M)|I|^2 \tag{2.35}$$

(2.33)-(2.35) indicate that total power loss per phase of a balanced line in a balanced system are all positive and equal, as anticipated.

F. A System Reduction Method to Estimate the Degree of System Unbalances

In large power networks, when the unbalanced study area comprises only a portion of the system, this method can be adopted to reduce the unimportant part of the system and retain only the area that is of interest, as far as the unbalances are concerned.

This method assumes all system elements, namely, transmission lines and loads outside the study area are balanced. Transmission lines, therefore, can be represented by decoupled series impedance and shunt impedance matrices in the symmetrical component frame of reference and loads by decoupled shunt impedance matrices also in the symmetrical component frame of reference.

In addition, this method is capable of determining the unbalanced load flow solution in the reduced system, assuming constant admittance load representations.

1. Model development

a. Generator with its step-up transformer   Generators are modeled in a way to be compatible with the 3-ϕ load-flow program model [4].

In this method, generator internal voltages are assumed to be balanced with constant magnitudes and angles that can be obtained from the results of 1-ϕ load-flow analysis. The assumption of constant angles indicates that the phase angle of the generator internal voltage obtained in an unbalanced case does not differ appreciably from that obtained in a balanced case which is believed to be fairly reasonable.

In regulated generators, regulation is assumed to be at generator terminal and the representation is shown in Figure 8.

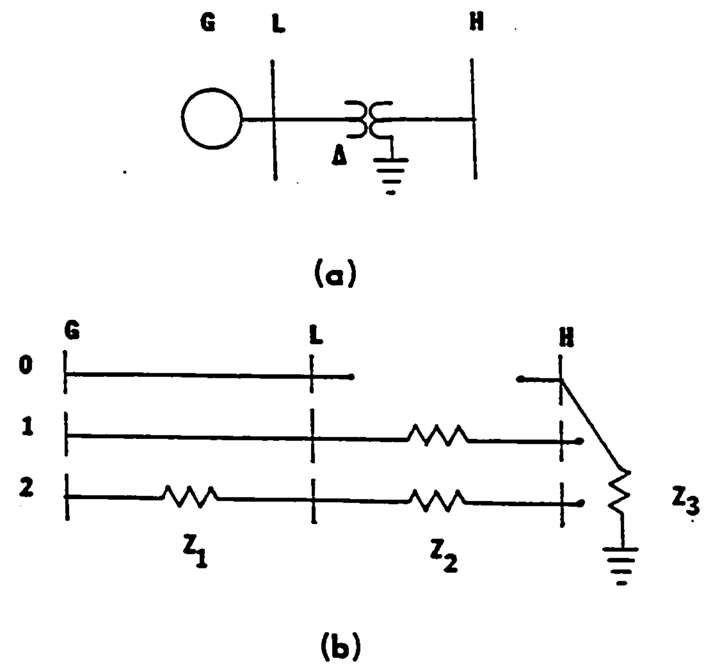

FIGURE 8. Representation of the regulated generator and its power transformer: (a) generator and its power transformer, (b) connection diagram

The positive sequence bus of the internal generator bus is solidly connected to its respective low-voltage (LV) bus, as it is intended to hold its voltage and angle constant at the LV bus. The zero sequence connection is immaterial since there is no zero sequence path involved;

however, for purposes of simplicity, a solid connection between the generator internal bus and LV bus is assumed. The negative sequence bus of the internal generator bus is connected to that of its LV bus through the generator negative sequence impedance. G to L connection is represented by Z_1

$$Z_1 = \begin{bmatrix} 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & Z_{m_2} \end{bmatrix}$$

where

Z_{m_2} = generator negative-sequence impedance

To represent the generator step-up transformer (Δ-Y connected), the positive and negative sequence generator LV buses are connected to the respective high-voltage (HV) buses through transformer positive and negative sequence impedances. The zero sequence connection is open. L to H connection is represented by Z_2

$$Z_2 = \begin{bmatrix} \infty & 0.0 & 0.0 \\ 0.0 & Z_{t_1} & 0.0 \\ 0.0 & 0.0 & Z_{t_2} \end{bmatrix}$$

where

Z_{t_1}, Z_{t_2} = positive-sequence and negative-sequence impedances of the transformer

The zero sequence generator HV bus is connected to ground if the transformer is solidly grounded on its HV side. This is represented by Z_3

$$Z_3 = \begin{bmatrix} Z_{t_0} & 0.0 & 0.0 \\ 0.0 & \infty & 0.0 \\ 0.0 & 0.0 & \infty \end{bmatrix}$$

where

Z_{t_0} = zero-sequence impedance of the transformer

Representation of the reference generator is very identical to that of the regulated generator except that the positive sequence bus of the reference bus is solidly connected to its HV bus, as it is intended to hold its voltage and angle constant at the HV bus. This is because the HV bus of the reference generator is assumed to be the slack bus in the 3-ϕ load-flow program. This representation is shown in Figure 9. The LR to HR connection is represented by Z_4

$$Z_4 = \begin{bmatrix} \infty & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & Z_{t_2} \end{bmatrix}$$

In generators representations, used in this method, the LV bus of generators are omitted, and generators are represented by their internal and HV nodes. The regulated generator internal bus to its HV bus connection, therefore, can be represented by Z_{GH}

$Z_{GH} = Z_1 + Z_2$

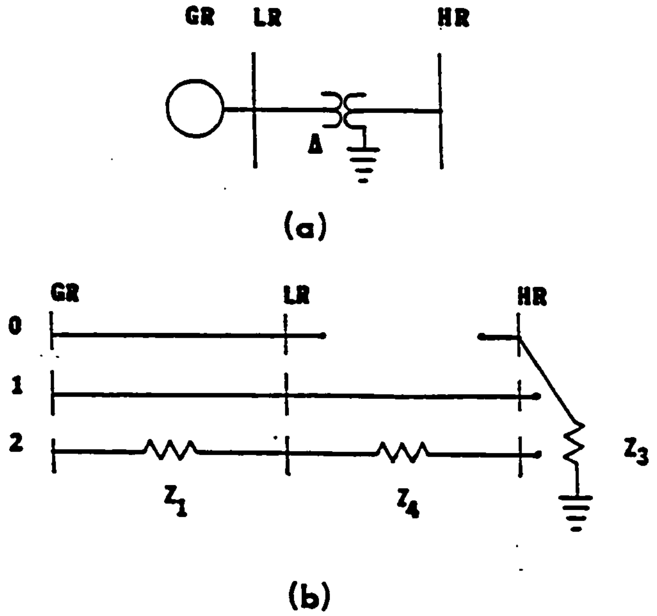

FIGURE 9. Representation of the reference generator and its power transformer: (a) generator and its power transformer, (b) connection diagram

$$Z_{GH} = \begin{bmatrix} \infty & 0.0 & 0.0 \\ 0.0 & Z_{t_1} & 0.0 \\ 0.0 & 0.0 & Z_{t_2}+Z_{m_2} \end{bmatrix}$$

This is shown in Figure 10.

The reference generator internal bus to its HV bus connection also can be represented by an equivalent impedance matrix $Z_{GR\text{-}HR}$

$Z_{GR\text{-}HR} = Z_1 + Z_4$

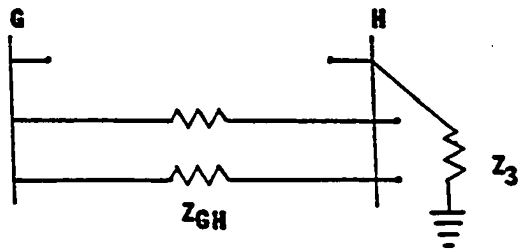

FIGURE 10. Simplified representation of the regulated generator and its power transformer

$$Z_{GR-HR} = \begin{bmatrix} \infty & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & Z_{t_2}+Z_{m_2} \end{bmatrix}$$

This representation is shown in Figure 11.

b. Transmission lines Transmission lines are represented by their equivalent series impedance and shunt admittance matrices in the symmetrical component frame of reference. These matrices are obtained from the conductor parameter program [29] by using the actual line configuration data.

Mutual couplings between the parallel lines are considered in this method. Since the system outside of the study area is assumed to be

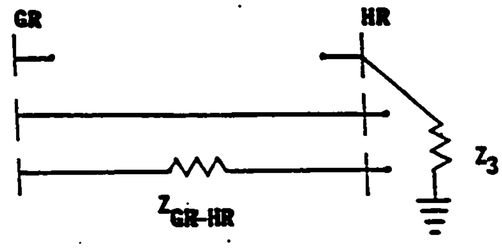

FIGURE 11. Simplified representation of the reference generator and its power transformer

balanced, mutual couplings therefore exist only in zero sequence impedances. In this case, first, the primitive impedance matrix for the zero sequence elements of the coupled lines is constructed, then inverted and included in the system Y-bus.

Mutual couplings between the lines inside of the study area, on the other hand, involves all sequence series impedances. Mutual couplings between the shunt admittances are neglected since their effects are negligible.

To represent the mutual couplings in the unbalanced study area, consider the two parallel lines shown in Figure 12.

The voltage drops in the lines in matrix form are

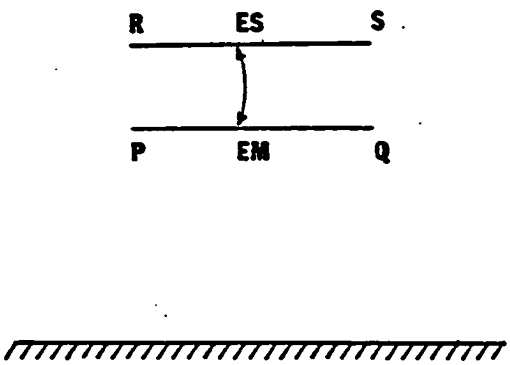

FIGURE 12. Two parallel lines above ground plane

$$\begin{bmatrix} V_{RS} \\ V_{PQ} \end{bmatrix} = \begin{bmatrix} Z_{RS} & Z_{M1} \\ Z_{M2} & Z_{PQ} \end{bmatrix} \begin{bmatrix} I_{RS} \\ I_{PQ} \end{bmatrix} \tag{2.36}$$

where

Z_{RS} = self impedance matrix (3x3) of line RS

Z_{M1} = mutual impedance matrix (3x3) between lines RS and PQ

Z_{M2} = mutual impedance matrix (3x3) between lines PQ and RS

Z_{PQ} = self impedance matrix (3x3) of line PQ

V_{RS} = voltage drop in line RS = $V_R - V_S$

V_{PQ} = voltage drop in line PQ = $V_P - V_Q$

I_{RS} = current in line RS

I_{PQ} = current in line PQ

The inverted form of (2.36) can be written as

$$\begin{bmatrix} I_{RS} \\ I_{PQ} \end{bmatrix} = \begin{bmatrix} Y_{RS} & Y_{M1} \\ Y_{M2} & Y_{PQ} \end{bmatrix} \begin{bmatrix} V_{RS} \\ V_{PQ} \end{bmatrix} \qquad (2.37)$$

Now, consider the two-port network shown in Figure 13.

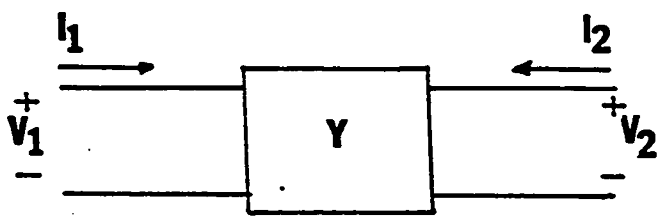

FIGURE 13. A two-port network

The currents in the matrix form can be written as

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad (2.38)$$

When there are no shunts

$I_1 = -I_2$

Hence, let

$$I_1 = \begin{bmatrix} I_{RS} \\ \\ I_{PQ} \end{bmatrix}$$

and

$$I_2 = -I_1 = \begin{bmatrix} I_{SR} \\ \\ I_{QP} \end{bmatrix}$$

$$V_1 = \begin{bmatrix} V_R \\ \\ V_P \end{bmatrix}$$

$$V_2 = \begin{bmatrix} V_S \\ \\ V_Q \end{bmatrix}$$

Expanding (2.37) and substituting for I_1, I_2, V_1, and V_2 in (2.38) will give

$$\begin{bmatrix} I_{RS} \\ I_{PQ} \\ I_{SR} \\ I_{QP} \end{bmatrix} \quad \begin{array}{c} \\ R \\ P \\ S \\ Q \end{array} \begin{array}{c} \begin{array}{cccc} R & P & S & Q \end{array} \\ \begin{bmatrix} Y_{RS} & Y_{M1} & -Y_{RS} & -Y_{M1} \\ Y_{M2} & Y_{PQ} & -Y_{M2} & -Y_{PQ} \\ -Y_{RS} & -Y_{M1} & Y_{RS} & Y_{M1} \\ -Y_{M2} & -Y_{PQ} & Y_{M2} & Y_{PQ} \end{bmatrix} \\ Y_{MUT} \end{array} \begin{bmatrix} V_R \\ V_P \\ V_S \\ V_Q \end{bmatrix} \tag{2.39}$$

Thus, to take the mutual couplings into consideration, each element of the matrix Y_{MUT} in (2.39) which itself is a (3x3) matrix should be added to the corresponding element of the 3-ϕ system Y-bus (e.g., Y-bus (R,S) = Y-bus (R,S) - Y_{RS}, etc.).

c. Loads To represent the balanced loads outside the study area, the equivalent circuit shown in Figure 14 is considered.

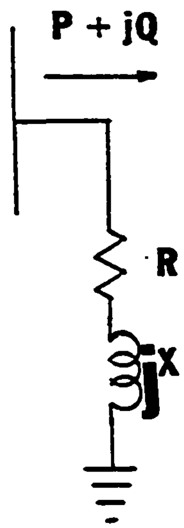

FIGURE 14. Load equivalent impedance to ground representation

It should be realized that since

$$MVA_{base}|_{1\phi} = 1/3\ MVA_{base}|_{3\phi}$$

the power per phase in pu is equal to the 3-ϕ power in pu. That is,

$$P_{pu} + jQ_{pu}|_{1\phi} = P_{pu} + jQ_{pu}|_{3\phi}$$

Power dissipated in R and X are

$P = R|I|^2$ MW/phase

and

$Q = X|I|^2$ MVAR/phase

It can be shown that

$$R = P|V_{LN}|^2/(P^2 + Q^2) \quad \text{Ohms} \tag{2.40}$$

and

$$X = Q|V_{LN}|^2/(P^2 + Q^2) \quad \text{Ohms} \tag{2.41}$$

where

V_{LN} = line to neutral voltage at the load bus in kV (known from the 1-ϕ load flow solution)

Let

$$FAC_1 = |V_{LN}|^2/(P^2 + Q^2) \quad A^{-2} \tag{2.42}$$

(2.42) in puA would be

$$FAC_2 = BMVA^2|V_{pu}|^2/(P_{3\phi}{}^2 + Q_{3\phi}{}^2) \quad \text{puA} \tag{2.43}$$

where

$P_{3\phi}, Q_{3\phi}$ = three-phase P and Q at the load in MW and MVAR, respectively

$V_{pu} = V_{LN}$/(system base voltage, kV line-to-neutral)

From (2.40) and (2.41), the equivalent load impedance can be written as

$$Z = R + jX = FAC_2 3(P + jQ)/BMVA \quad \text{pu}$$

or in a more systematic way

$$Z = \text{FAC}(P_{3\phi} + jQ_{3\phi}) \quad \text{pu} \tag{2.44}$$

where

$$\text{FAC} = \text{BMVA}|V_{pu}|^2/(P_{3\phi}^{\;2} + Q_{3\phi}^{\;2})$$

Equation (2.44) is incorporated in the computer program developed for this method. By simply entering the total 3-ϕ power in MVA and bus voltage in puV at the load, the program will compute the load equivalent impedance and no external computation thus will be necessary.

To represent the loads (balanced or unbalanced) inside the study area, the equivalent circuit shown in Figure 15 is considered.

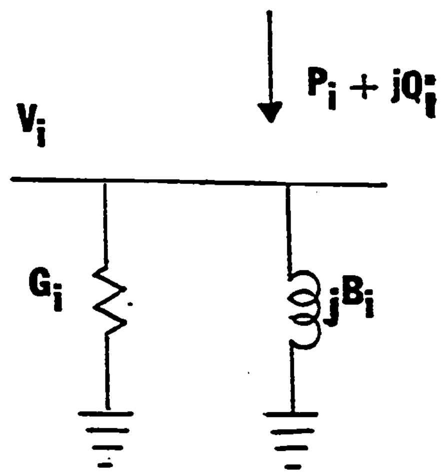

FIGURE 15. Phase i equivalent load admittance to ground representation

Let

$S_i = P_i + jQ_i$ MVA/phase for i=a,b,c

$V = (|V_a| + |V_b| + |V_c|)/3$ puV

V in an unbalanced system, therefore, is assumed to be approximately the same as V obtained from a balanced 3-ϕ representation.

The equivalent load G and B in each phase is

$G_i = 3P_i/(V^2 BMVA)$ pu

and $B_i = 3Q_i/(V^2 BMVA)$ pu

or

$$G_i - jB_i = (P_i - jQ_i)/FAC_2 \quad \text{pu} \tag{2.45}$$

where

$FAC_2 = V^2 BMVA/3$

P_i and Q_i are expressed in MW and MVAR, respectively.

Equation (2.45) is also incorporated in the program. By entering the per phase power (P in MW and Q in MVAR) and voltage magnitude in puV known from the results of 1-ϕ load-flow analysis, the program will compute the equivalent load admittance to ground for each phase.

d. Transformers The equivalent matrix Z_2 is used to represent the Δ-Δ, Δ-Y, and Y-Y connected transformers. The equivalent matrix Z_3 is used, in addition to Z_2, to represent the Δ-Y grounded and Y-Y grounded transformers. Y grounded-Y grounded transformers are represented by

$$Z_t = \begin{bmatrix} Z_{t_0} & 0.0 & 0.0 \\ 0.0 & Z_{t_1} & 0.0 \\ 0.0 & 0.0 & Z_{t_2} \end{bmatrix}$$

Three-winding transformers, although not considered in this method, can be modeled using the equivalent star representation.

2. General features of the FORTRAN computer program

A general FORTRAN computer program has been developed for this method. The program user must number the nodes in sequence and grouped in the following order:

I. Edge of study area nodes

II. Inside of study area nodes

III. Internal nodes of the generators inside of study area

IV. Internal nodes of the generators outside of study area

V. Outside of study area nodes

The system reduced Y-bus is formed in 4 steps as shown in Figures 16-19. Group III nodes are connected to group I nodes.

In the first step, the three sequence Y-buses, namely, zero-sequence, positive-sequence, and negative-sequence decoupled matrices are constructed leaving out all group II nodes and leaving out all connections to group II nodes. In the second step, the program Kron reduces these Y-buses individually by removing all group V nodes. In the third step, the three reduced Y-buses are combined and a 3-ϕ Y-bus is formed. The 3-ϕ Y-bus is made up of 3x3 submatrices, each of which is an 0,1,2 matrix. Finally, in the fourth step, inside of study area nodes, group II, and all the elements connected to the group II nodes are added to the 3-ϕ Y-bus. Each element is represented by a 3x3

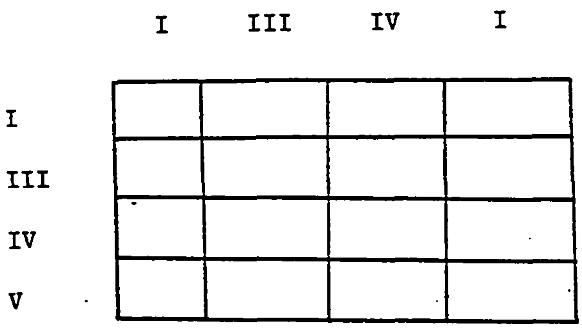

FIGURE 16. Structure of the zero-sequence, positive-sequence, and negative-sequence Y-buses before including group II, inside of study area nodes

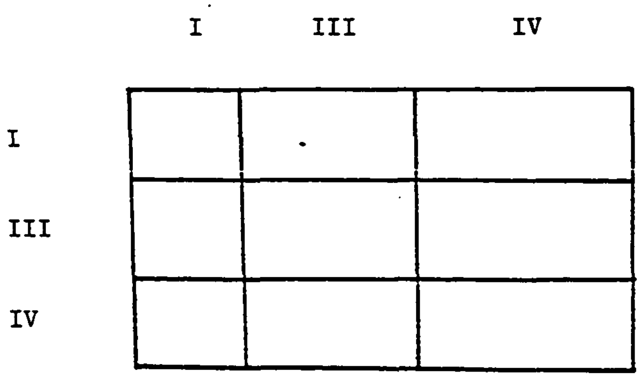

FIGURE 17. Structure of the Kron reduced version of the three-sequence Y-buses

	I	II	III	IV
I				
II				
III				
IV				

FIGURE 18. Structure of the 3-ϕ Y-bus after including inside of study area nodes

matrix. At the end of this step, the 3-ϕ symmetrical component Y-bus is complete, representing both the reduced equivalent of the outside of study area nodes and inside of study area with its unbalanced elements.

Now, by applying the known positive sequence voltages at the internal nodes of the generators, the system equations can be solved to determine the unknown voltages. To do this, the matrix shown in Figure 18 is divided into 4 submatrices Y1, Y2, Y3, and Y4. This is shown in Figure 19.

The system equations can then be written as

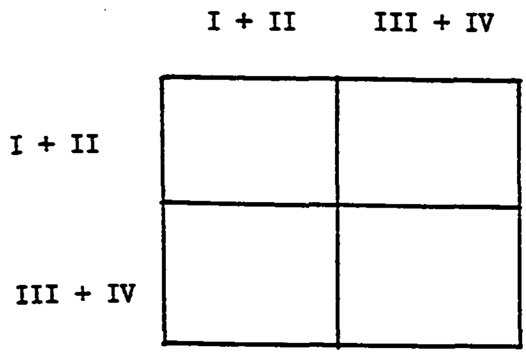

FIGURE 19. Structure of the 3-ϕ Y-bus divided into four submatrices

$$\begin{bmatrix} 0 \\ \hline I_g \end{bmatrix} = \left[\begin{array}{c|c} Y_1 & Y_2 \\ \hline Y_3 & Y_4 \end{array}\right] \begin{bmatrix} V \\ \hline V_g \end{bmatrix}$$

This will give

$$0 = Y_1 V + Y_2 V_g$$

or

$$V = -Y_1^{-1} Y_2 V_g \tag{2.46}$$

where

V = unknown voltage vector

V_g = known voltage vector consisting of the internal nodes of the generators in order of III and IV

With voltages computed from (2.46), the line currents and power flows will then be computed by the program.

This program can be used to reduce a system with up to 50 generators, 100 buses, 300 elements (single-circuit lines, line chargings, shunts, loads, transformers, etc.), and 20 coupled transmission lines. The unbalanced voltages, line currents, and power flows will then be computed in the reduced system. The reduced system may consist of up to 30 buses, 65 elements, and 10 coupled lines.

Efforts have been made to make the data preparation and data handling simple and to keep computation time to a minimum. For this purpose, a type number is assigned to each new element and therefore the element needs to be entered once in the data file. The value of element (impedance if the element is in the outside of study area or admittance matrix if the element is inside of study area) along with its type number will be stored in the memory. The value of the element, therefore, can be referenced later in the program by only referring to its type number. For instance, for transmission lines outside of study area, the series and shunt impedances for each line configuration entered in per unit Ohms/mile can be identified later in the program by its type numbers (two different type numbers should be assigned to series impedances and shunt admittances).

In constructing the Y-buses, a line in the system thus can be identified by its type numbers, connecting node numbers, and the length of the line in miles. This would not only reduce errors involved in data entering, it also makes data handling convenient, particularly, when dealing with the data inside the study area.

As far as savings in computer time is concerned, since the program uses a Y-bus algorithm, there is no major inversion of matrices except in computing the voltages (see 2.46) and Kron reduction segment of the program. Taking advantage of sparse Y-bus matrices, the time involved in this procedure has been kept to a minimum.

Listing of the FORTRAN program with sample input data formats are presented in Appendix II.

III. RESULTS OF THE STEADY-STATE ANALYSIS

A. Introduction

In order to demonstrate the significance of system unbalances, a hypothetical EHV test system will be studied under various unbalanced conditions. Although this is not an existing system, its components are chosen so they may represent a practical EHV transmission system.

For this study, the full 3-ϕ representation of the system will be obtained and the 3-ϕ load-flow program will be used to determine the 3-ϕ steady-state solutions.

Furthermore, the impact of various system parameters, namely, the length of untransposed lines and the system loading on the unbalances will be evaluated, the criteria for unbalanced loads obtained in Chapter II will be examined, and the effect of power coupling on power flows will be demonstrated.

Finally, comparisons between the 3-ϕ load-flow program and the newly developed system reduction method will be conducted to demonstrate the practical application of this method.

B. Study of a 24-Bus EHV Test System

A single line diagram of a hypothetical 24-bus EHV test system consisting of 6 generators, 9 loads, 25 single-circuit lines, 2 double-circuit lines, along with their phase arrangements, is shown in Figure 20.

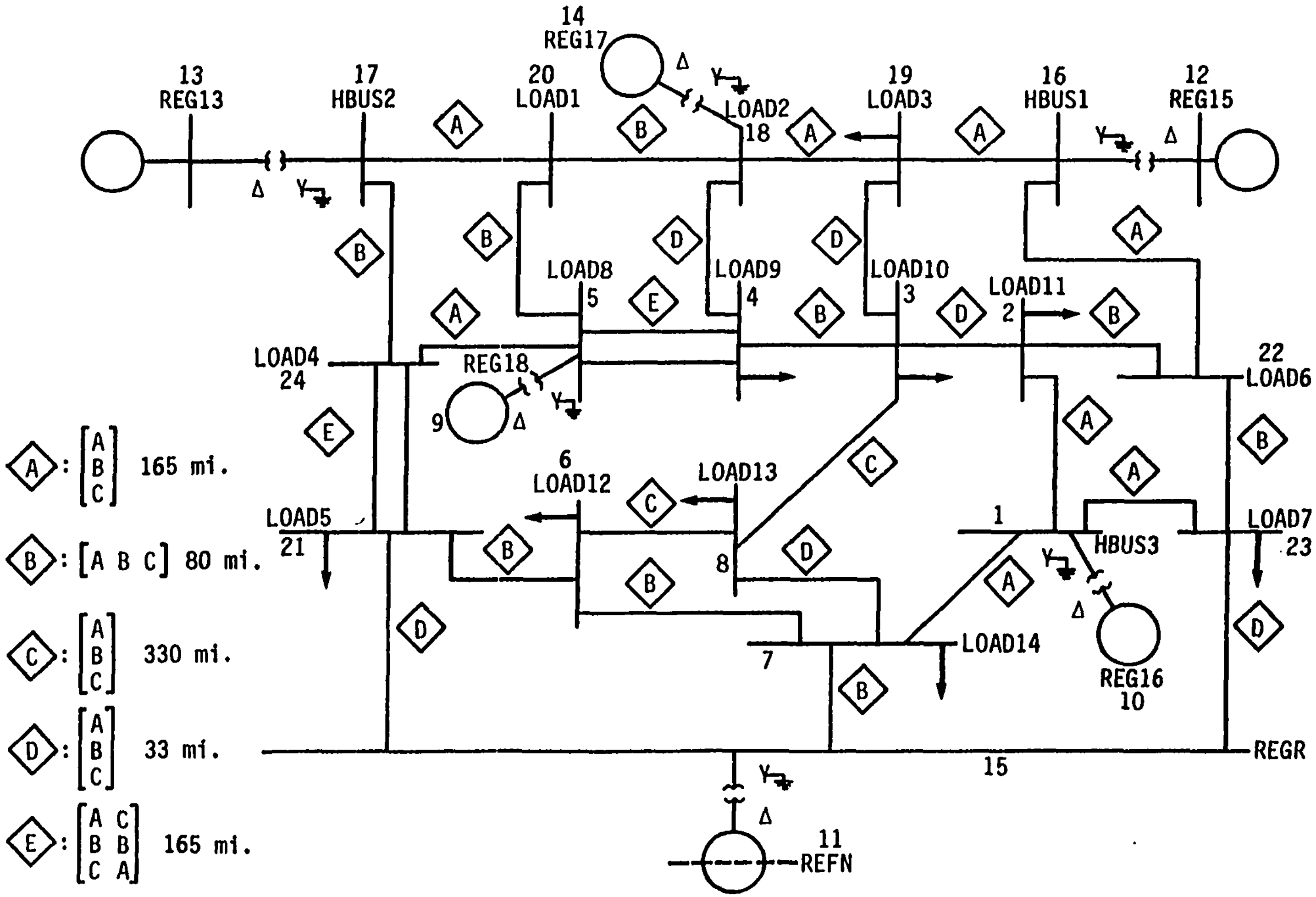

FIGURE 20. 24-Bus EHV test system

The full 3-ϕ representation of the system with the mutual coupling between the parallel lines and the load unbalances is considered in this study.

Four cases are considered in this analysis:

1. Balanced network, balanced bus loading.
2. Unbalanced network, balanced bus loading.
3. Balanced network, unbalanced bus loading.
4. Unbalanced network, unbalanced bus loading.

The unbalanced network is obtained by leaving all transmission lines untransposed (see Figure 21, Table 1 for line configurations, and Table 2 for machine data). The line configurations for types C and D are similar to that for type A.

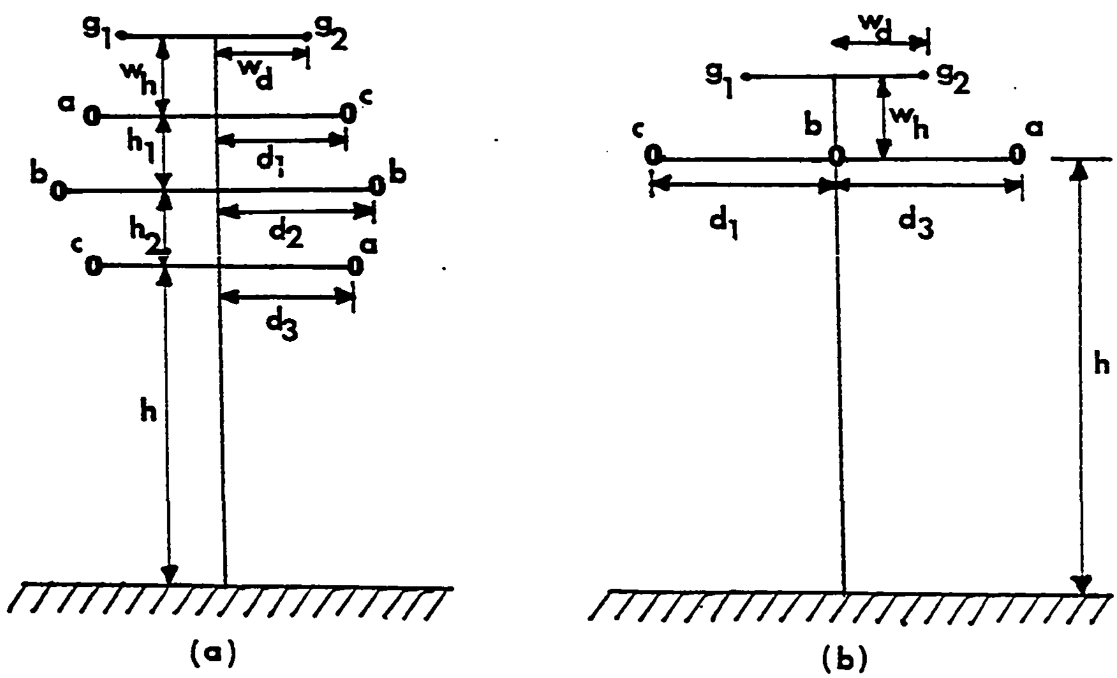

FIGURE 21. Line configuration: (a) vertical single circuit and double circuit, (b) horizontal single circuit

TABLE 1. Transmission line dimensions in feet

TYPE	h	h_1	h_2	w_h	d_1	d_2	d_3	w_d	Conductor	Static
A[a]	36.33	25.5	24.5	26.34	19.33	26.83	20.33	12	954 MCM ACSR Bundled 18" Spacing	159 MCM ACSR
B[b]	40.38	-	-	35.45	-24.5	-	24.5	16.5	2156 MCM ACSR	steel 7/16"
E[a]	36.33	25.5	24.5	26.34	19.33	26.83	20.33	12	Twin 954 MCM ACSR Bundled 18" Spacing	159 MCM ACSR

[a] See Figure 21a.
[b] See Figure 21b.

The unbalanced loading network is obtained by representing the two 3-ϕ loads a buses LOAD11 and LOAD13 unbalanced. This is done based on the assumption that total 3-ϕ system loading remains constant and equal to that in a balanced case (case1).

The balanced operating conditions of the system used in the analysis are shown in Tables 3a and 3b.

The unbalanced operating conditions are the same as the balanced conditions except for the unbalanced loading on buses LOAD11 and LOAD13. This is shown in Table 4.

TABLE 2. Machine data

GENERATOR	RATED KV	RATED MVA	GENERATOR REACTANCE, PU ON A 100-MVA BASE $X_{G_0}=X_{G_1}=X_{G_2}$
REG13	18	410	.0211
REG17	18	200	.0211
REG16	18	280	.0211
REG18	18	300	.0211
REG15	18	300	.0211
REFN	18	1200	.0211

TABLE 3a. 24-Bus EHV test system balanced operating conditions: GENERATION

GENERATOR	DISPATCH VOLTAGE, KV	TOTAL 3-Φ POWER MW
REG13	345	360
REG17	345	60
REG16	345	160
REG18	345	200
REG15	345	60
REGR[a]	345	
REFN[b]	345	

[a] Swing Bus (1-Φ Load Flow Program).
[b] Swing Bus (3-Φ Load Flow Program).

The base quantities used in this study are:

Base voltage = 345 kV

Base $MVA_{3\phi}$ = 100.0 MVA

Base $MVA_{1\phi}$ = 33.33 MVA

Base current = 167.0 A

The maximum unbalanced currents and voltages obtained for the four cases considered are given in Tables 5-7. As is shown in Table 5, the maximum voltage unbalance exists at bus LOAD13. This may be due to the fact that LOAD13 is connected to 3 untransposed lines, two of which are relatively long (330.0 mi. each).

TABLE 3b. 24-Bus EHV test system balanced operating conditions: LOAD

LOAD BUS	Phase a MW	MVAR	Phase b MW	MVAR	Phase c MW	MVAR
LOAD2	0.0	30.0	0.0	30.0	0.0	30.0
LOAD5	30.0	10.0	30.0	10.0	30.0	10.0
LOAD14	80.0	30.0	80.0	30.0	80.0	30.0
LOAD7	40.0	30.0	40.0	30.0	40.0	30.0
LOAD3	60.0	40.0	60.0	40.0	60.0	40.0
LOAD9	30.0	20.0	30.0	20.0	30.0	20.0
LOAD11	50.0	30.0	50.0	30.0	50.0	30.0
LOAD6	0.0	40.0	0.0	40.0	0.0	40.0
LOAD12	80.0	35.0	80.0	35.0	80.0	35.0
LOAD11	50.0	30.0	50.0	30.0	50.0	30.0
LOAD13	90.0	60.0	90.0	60.0	90.0	60.0

TABLE 4. Unbalanced bus loading

LOAD BUS	Phase a MW	MVAR	Phase b MW	MVAR	Phase c MW	MVAR
LOAD11	10	10	100	50	40	30
LOAD13	20	10	120	80	130	90

In the case of an unbalanced network, maximum zero-sequence voltage as high as 2% and negative-sequence voltage as high as 3% of the positive-sequence voltage exists at LOAD13. These components increased to 20% and 12% of the positive-sequence voltage when the loads were unbalanced. Maximum zero sequence current due to untransposed transmission lines was found to be on the order of 0.1 puA on line LOAD14-LOAD13 (see Table 6). Although this much current unbalance does not appear to be significant, it should be realized that it does not represent the maximum zero sequence current that can exist in the system. In other words, based on the discussion given in section C of Chapter II, higher unbalances would have been obtained if system loading were higher. With loads being unbalanced, however, the magnitude of this current increased to 1.2 puA. This is of great interest as far as ground overcurrent relays are concerned.

Table 7 shows the maximum generator current unbalance that turns out to occur at REFN generator. Negative sequence current as high as 0.5 puA exists at this generator when all transmission lines are left untransposed. This current increased to 1.4 puA when two loads in the system (LOAD11 and LOAD13) were represented unbalanced. This is of great concern because of its effect on heating of the rotor.

The point of presenting this example was to demonstrate the importance of full 3-ϕ representation in the steady-state analysis. In general, there is no simple way of determining the location and the degree of maximum unbalance in the system. The only possible way of obtaining this would be the 3-ϕ analysis of the system that takes into account the overall effect of the transmission network and the load.

TABLE 5. Maximum voltage unbalance (at LOAD13)

CASE NO.	$V_{0,1,2}$, puV	$V_{a,b,c}$, puV
1	0.0 1.082 /_-11.1 0.0	1.082 /_-11.1 1.082 /_-131.1 1.082 /_108.9
2	0.0194 /_109.3 1.081 /_-11.1 0.033 /_143.5	1.043 /_-9.41 1.098 /_-131.0 1.103 /_107.3
3	0.212 /_20.3 1.057 /_-11.38 0.136 /_28.3	1.358 /_-2.97 0.894 /_-133.5 0.950/_98.6
4	0.208 /_27.1 1.055 /_-11.05 0.122 /_43.0	1.310/_-1.05 0.912 /_-133.2 0.982 /_97.61

In the next section, the sensitivity of the network unbalances to the variation in the length of untransposed lines and the system loading in the test system will be determined, and the significance of unbalances that can be caused by different types of unbalanced loads will be examined. In addition, some examples will be provided to demonstrate the effect of power coupling phenomena.

TABLE 6. Maximum line current unbalance (line LOAD14-LOAD13)

CASE NO.	$I_{0,1,2}$, puA	$I_{a,b,c}$, puA
1	0.0 2.422 $\angle$26.41 0.0	2.422 $\angle$26.41 2.422 $\angle$-93.6 2.422 $\angle$146.4
2	0.085 $\angle$-167.9 2.424 $\angle$26.51 0.220 $\angle$-148.3	2.123 $\angle$26.5 2.542 $\angle$-90.8 2.613 $\angle$143.9
3	1.200/122.7 2.289 $\angle$16.04 1.490 $\angle$124.3	2.957 $\angle$76.0 3.154 $\angle$-125.8 2.824 $\angle$106.6
4	1.210 $\angle$127.8 2.287 $\angle$17.27 1.509 $\angle$133.93	2.753 $\angle$81.8 3.191 $\angle$-121.5 3.030 $\angle$108.5

C. Calculated Results

1. Effect of the length of untransposed transmission line on network unbalances

To determine the relation between the network unbalances and the length of transmission lines, the length of all the lines in the network was varied by -90% to 10% of the original lengths used in the base case (see Figure 20).

For the system considered, an increase of more than 10% in the length of lines would cause the 3-ϕ load-flow to diverge. This is because the reactive power required in the system could be supplied only by the generators since the system loading (including capacitive and reactive shunts) is kept unchanged throughout this study.

TABLE 7. Maximum generator current unbalance (at REFN)

CASE NO.	$I_{0,1,2}$, puA	$I_{a,b,c}$, puA
1	0.0 8.906 $\angle$3.9 0.0	8.906 $\angle$3.9 8.906 $\angle$-116.1 8.906 $\angle$123.89
2	0.0 8.919 $\angle$4.0 0.523 $\angle$-124.5	8.600$\angle$1.277 8.741 $\angle$-112.81 9.436 $\angle$123.5
3	0.0 8.679 $\angle$0.0 1.385 $\angle$147.4	7.549 $\angle$5.67 9.929 $\angle$-116.3 8.726 $\angle$110.87
4	0.0 8.723 $\angle$0.47 1.484 $\angle$168.9	7.276 $\angle$2.82 9.772 $\angle$-113.0 9.299 $\angle$111.76

The sequence components of the unbalanced currents induced in the generators are shown in Table 8. Five lines with the least and the most significant unbalanced currents were monitored. The sequence components of these line currents are shown in Table 9. The magnitude of I_0's and I_2's in Tables 8 and 9 is plotted and is shown in Figures 22-26.

It is clear from Tables 8 and 9 and Figures 22-26 that unbalances increase in magnitude with the length of untransposed lines in the network. One may notice that the angle on the positive sequence component of the current changes by substantial amount, whereas other angles change very little. Although the proof of this is not presented here, however, it can easily be shown that the change in the angle of

TABLE 8. Sequence components of the unbalanced current at the generators ($I_{0,1,2}$ puA) for various lengths of untransposed transmission lines in the network

	% Increase in Lines Lengths			
	-90	-50	0	10
GENERATORS	$I_{0,1,2}$, puA			
	0.0	0.0	0.0	0.0
REG13	3.617/_-31.0	3.611/_-17.6	3.901/_2.77	4.011/_6.7
	0.033/_-162.3	0.159/_-149.8	0.329/_-139.0	0.369/_-137.5
	0.0	0.0	0.0	0.0
REG17	0.850/_-74.5	0.612/_-41.6	1.747/_38.2	2.173/_42.0
	0.036/_-115.0	0.157/_-114.5	0.349/_-115.8	0.397/_-116.3
	0.0	0.0	0.0	0.0
REG16	1.658/_-43.8	1.604/_-26.4	2.740/_21.8	3.220/_27.3
	0.031/_-105.6	0.173/_-111.1	0.425/_-114.9	0.491/_-115.9
	0.0	0.0	0.0	0.0
REG18	2.067/_-42.3	2.007/_-22.8	2.869/_173.0	3.210/_22.74
	0.034/_-101.4	0.151/_-106.3	0.339/_-112.6	0.387/_-113.9
	0.0	0.0	0.0	0.0
REG15	0.817/_-72.5	0.602/_-27.8	1.883/_36.9	2.288/_39.9
	0.035/_-101.4	0.151/_-106.3	0.339/_-112.6	0.387/_-113.9
	0.0	0.0	0.0	0.0
REFN	9.845/_-72.7	7.300/_-32.7	8.919/_4.00	9.677/_9.831
	0.016/_-132.4	0.187/_-126.7	0.523/_-124.5	0.612/_-124.6

the positive sequence current due to change in the length of untransposed lines is more significant than the change in other angles.

TABLE 9. Sequence components of the unbalanced line currents ($I_{0,1,2}$ puA) for various lengths of untransposed transmission lines in the network

	% Increase in Lines Lengths			
	-90	-50	0	10
LINES		$I_{0,1,2}$, puA		
LOAD14-LOAD13				
	0.0086/_-157.3	0.03/_-161.6	0.085/_-167.9	0.107/_-171.0
	2.588/_-36.0	2.142/_-11.8	2.424/_26.5	2.664/_34.1
	0.014/_-141.3	0.083/_-149.0	0.219/_-148.3	0.258/_-148.8
LOAD12-LOAD13				
	0.0068/_-166.4	0.034/_-177.1	0.083/_-179.7	0.098/_179.6
	0.239/_-10.6	0.688/_65.20	1.626/_73.0	1.865/_73.5
	0.011/_-149.0	0.066/_-152.0	0.168/_-151.5	0.196/_-151.7
HBUS3-LOAD14				
	0.0090/_-28.90	0.012/_-150.0	0.048/_-176.9	0.062/_179.3
	1.201/_-9.00	1.177/_-0.67	1.520/_38.1	1.712/_45.1
	0.010/_-178.0	0.077/_-147.7	0.198/_-147.2	0.231/_-148.1
LOAD5-LOAD12				
	0.0048/_-154.5	0.012/_158.90	0.038/_169.90	0.052/_170.2
	2.957/_-23.2	2.732/_-6.77	2.848/_19.0	2.974/_25.1
	0.012/_-148.2	0.078/_-156.6	0.197/_-153.5	0.229/_-153.7
LOAD13-LOAD10				
	0.0086/_-166.1	0.034/_178.40	0.080/_176.50	0.090/_176.7
	0.378/_179.7	0.805/_112.4	1.417/_93.2	1.563/_90.4
	0.006/_-119.9	0.040/_-150.4	0.103/_-153.9	0.121/_-153.8

2. Effect of system loading on network unbalances

To determine the effect of system loading on the unbalances due to untransposed lines, system loading was increased from 0% to 60% of the original system loading used in the base case (see Table 10). In this

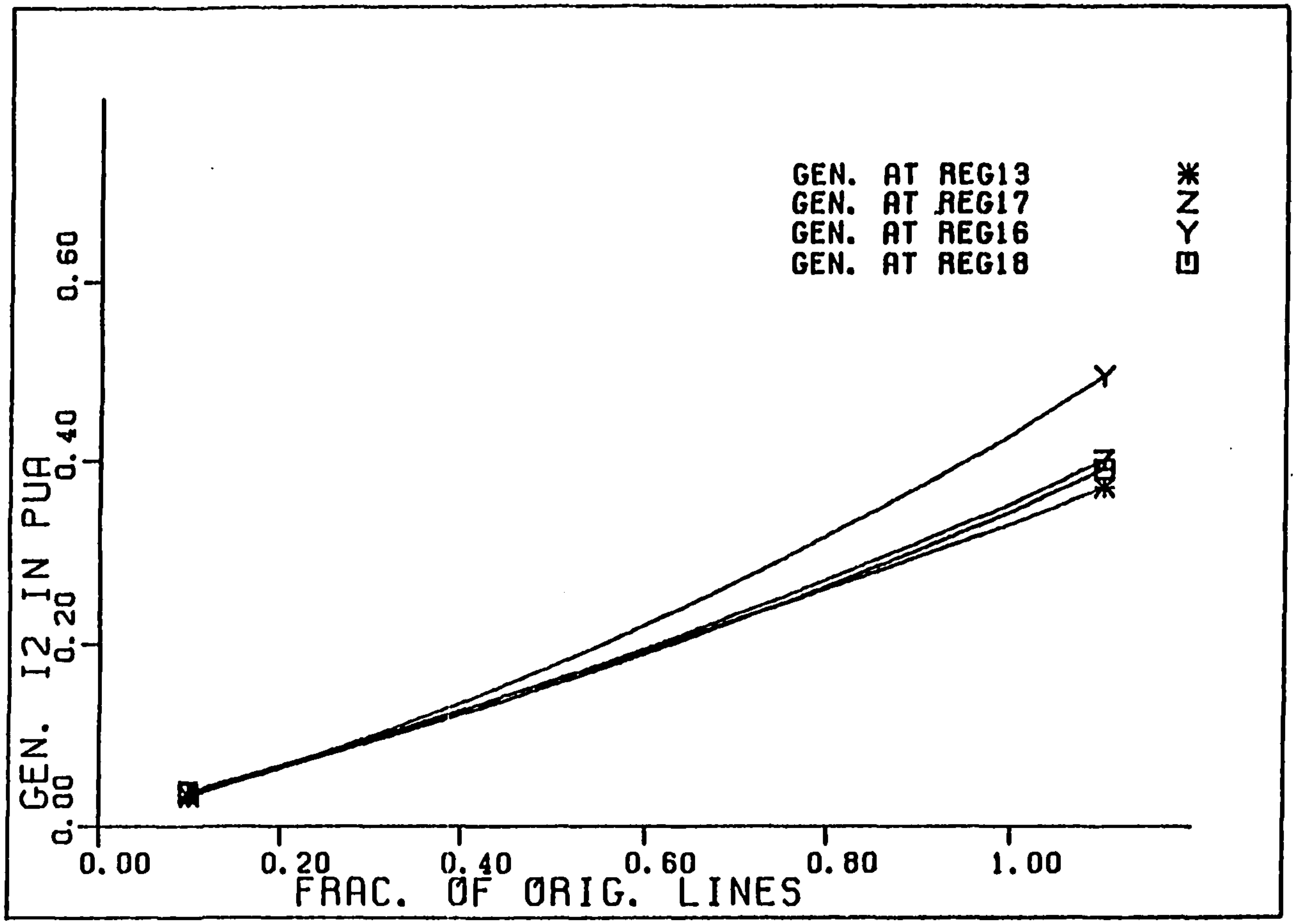

FIGURE 22. Relation between the negative-sequence currents induced in the generators with variations in the length of untransposed transmission lines - part 1

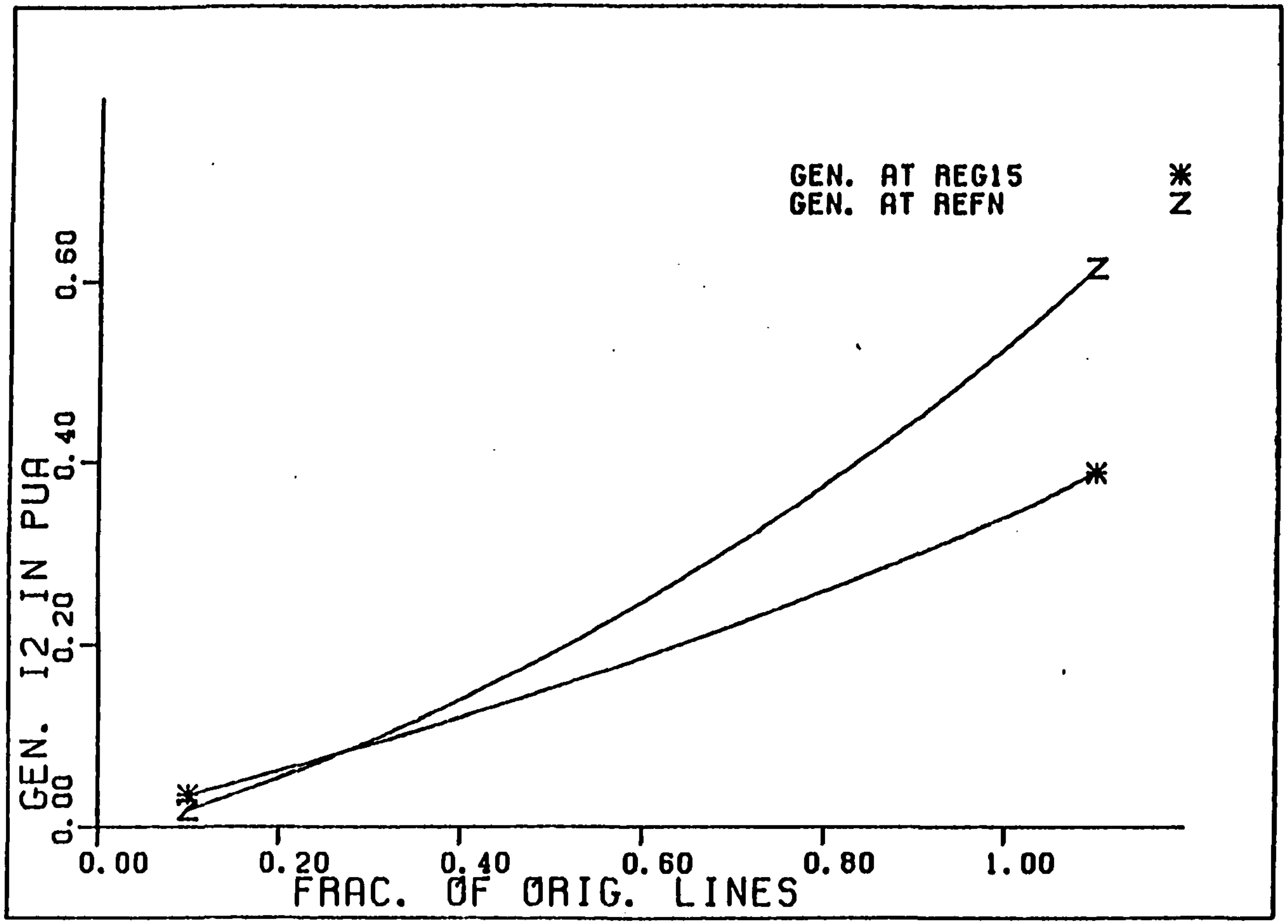

FIGURE 23. Relation between the negative-sequence currents induced in the generators with variations in the length of untransposed transmission lines - part 2

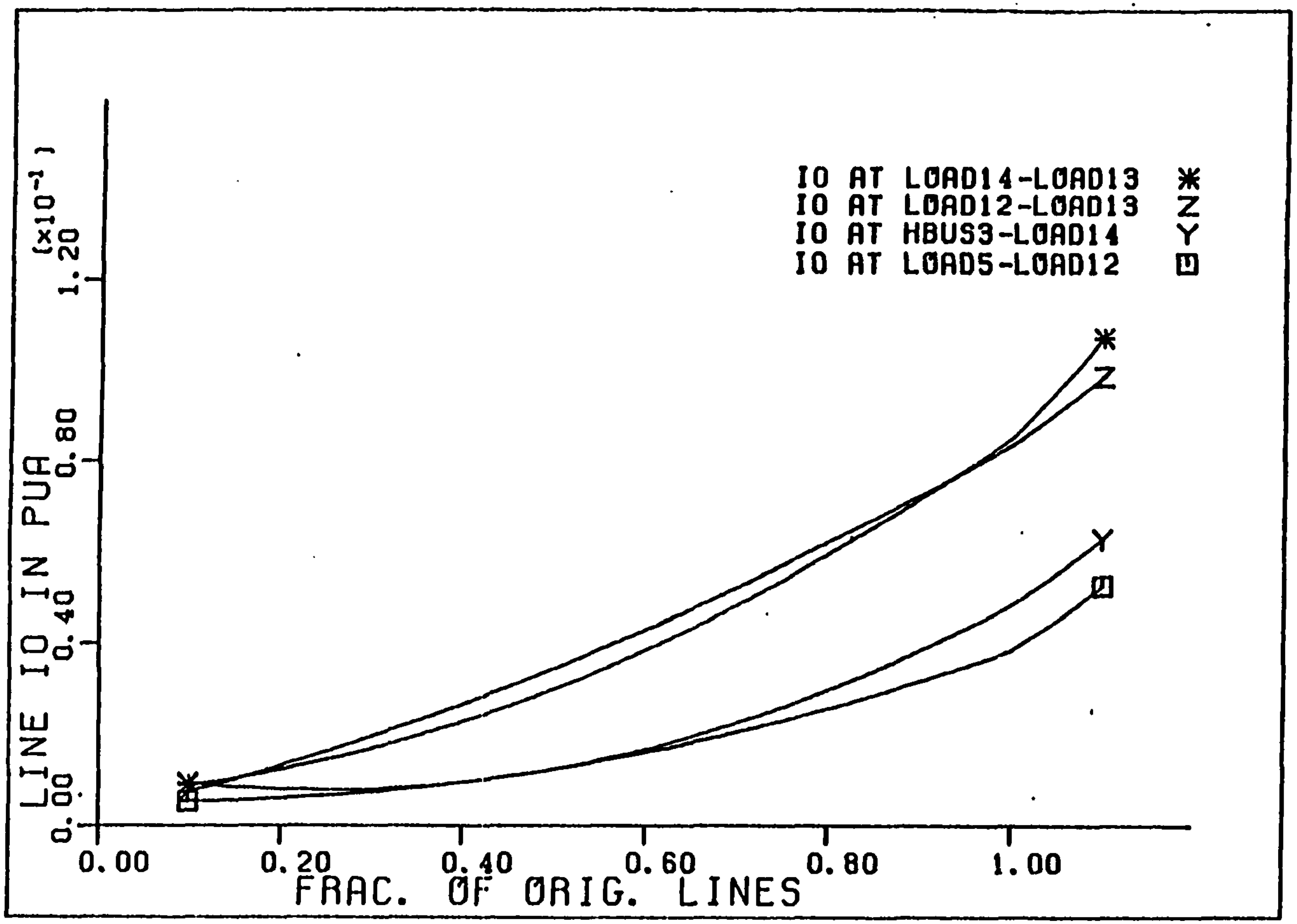

FIGURE 24. Relation between the zero-sequence component of the unbalanced line currents with variations in the length of untransposed transmission lines

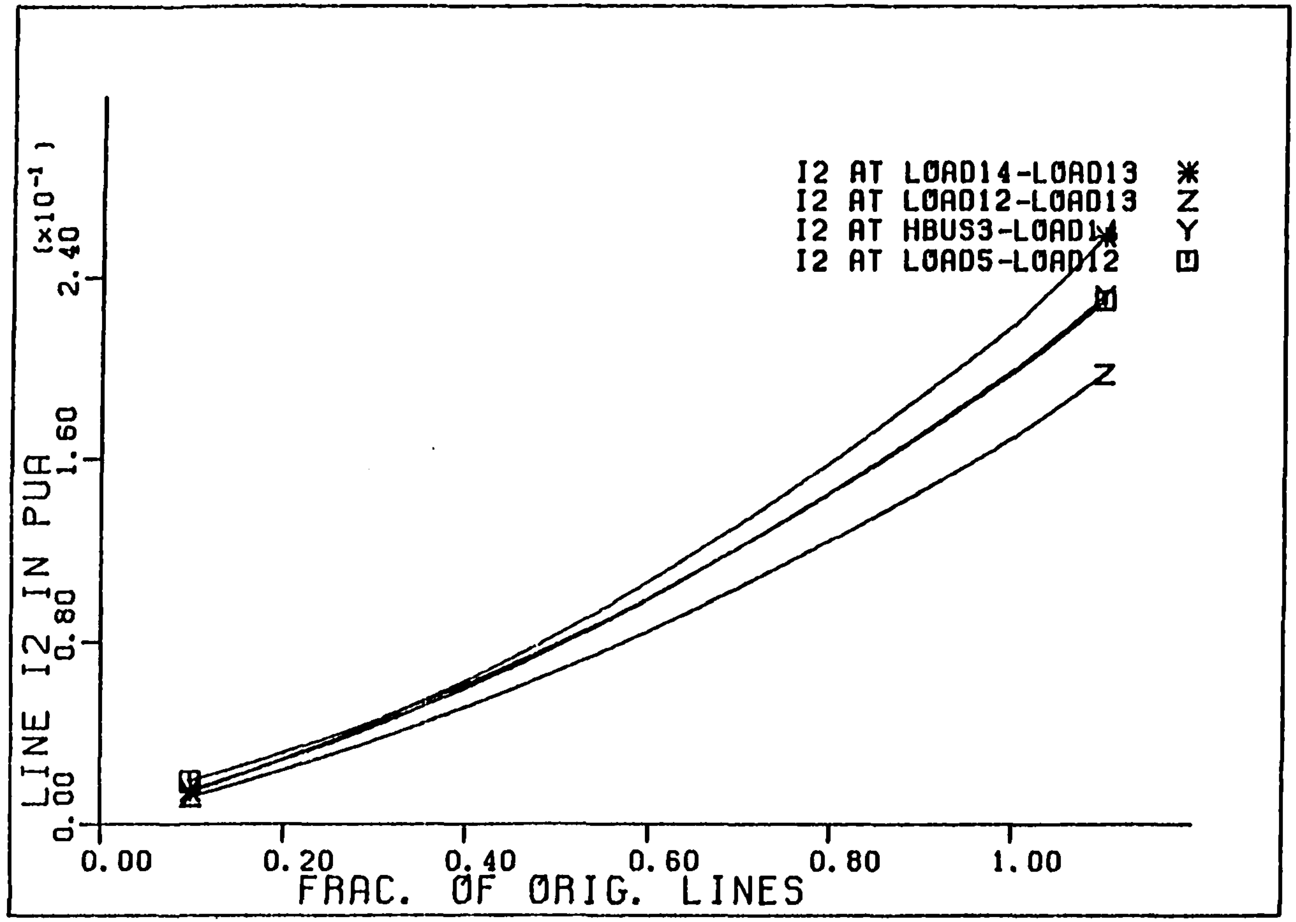

FIGURE 25. Relation between the negative-sequence component of the unbalanced line currents with variations in the length of untransposed transmission lines

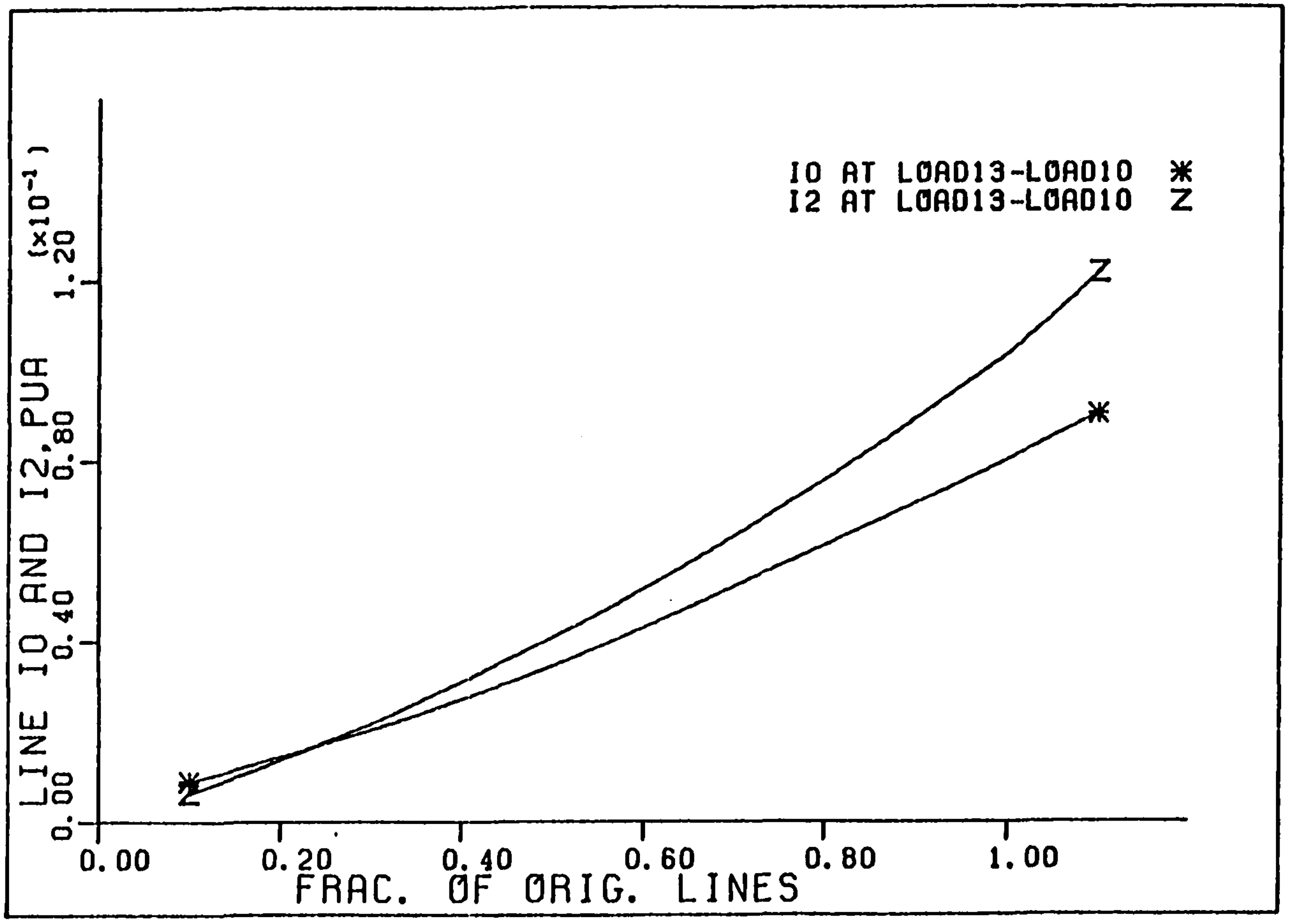

FIGURE 26. Relation between the zero-sequence and negative-sequence components of the unbalanced line currents with variations in the length of untransposed transmission lines

case, also, an increase of more than 60% in system loading would cause the 3-ϕ load-flow program to diverge. The convergence problem may be solved by adding another generator to the system. Since this would change the base case, it was not performed.

TABLE 10. Variations in system loading

	% Increase in System Loading				
	0	10	30	50	60
LOAD	ACTIVE POWER/PHASE, MW				
LOAD3	60	66	78	90	96
LOAD5	30	33	39	45	48
LOAD7	40	44	52	60	64
LOAD9	30	33	39	45	48
LOAD10	60	66	78	90	96
LOAD11	50	55	65	75	80
LOAD12	80	88	104	120	128
LOAD13	90	99	117	135	144
LOAD14	80	88	104	120	128

The variations in system loading are shown in Table 10. To ensure convergence, only the active power of the loads were increased. As far as the system generation is concerned, a uniform increase in generator scheduled power is assumed. This is shown in Table 11.

TABLE 11. Variations in system generation

	% Increase in System Generation				
	0	10	30	50	60
GENERATOR	TOTAL 3-Φ POWER, MW				
REG13	360	396	468	540	576
REG15	60	66	78	90	96
REG16	160	176	208	240	256
REG17	60	66	78	90	96
REG18	200	220	260	300	320

The sequence components of the currents induced in the generators are shown in Table 12. The sequence components of the unbalanced line currents for the five lines considered in the previous section are shown in Table 13. The magnitude of I_0's and I_2's in Tables 12 and 13 is plotted and is shown in Figures 27-31.

From Table 12, an increase of about 14% is observed in I_2 at generator REG16 for an increase of 60% in the system loading. No appreciable change was observed in I_2 at other generators in the cases considered (see also Figures 27 and 28). Negative sequence components of the line currents increased somewhat with the increase in system loading. The zero sequence currents, however, had a larger increase as the system loading increased (see Table 13 and Figures 29-31). Although in this case the zero-sequence components' increases seem to be

TABLE 12. Sequence components of the unbalanced current at the generators ($I_{0,1,2}$ puA) for variations in system loading

GENERATOR	% Increase in System Loading: 0	10	30	50	60
	$I_{0,1,2}$, puA				
REG13	0.0	0.0	0.0	0.0	0.0
	3.90/_2.710	4.20/_0.780	4.82/_-2.39	5.47/_-4.75	5.80/_-5.72
	0.33/_-139.0	0.33/_-140.2	0.33/_-141.1	0.32/_-137.6	0.30/_-129.8
REG17	0.0	0.0	0.0	0.0	0.0
	1.74/_38.21	1.70/_35.30	1.60/_28.70	1.50/_20.70	1.44/_15.81
	0.34/_-115.8	0.34/_-114.6	0.34/_-110.6	0.34/_-101.3	0.35/_-90.70
REG16	0.0	0.0	0.0	0.0	0.0
	2.74/_21.81	2.78/_17.96	2.86/_10.20	2.97/_2.390	3.03/_-1.69
	0.42/_-114.9	0.42/_-113.2	0.42/_-107.3	0.44/_-9.400	0.48/_-80.00
REG18	0.0	0.0	0.0	0.0	0.0
	2.89/_17.25	2.92/_13.65	3.11/_6.900	3.45/_0.500	3.50/_-2.57
	0.34/_-118.1	0.34/_-117.2	0.33/_-113.7	0.33/_-104.6	0.34/_-93.50
REG15	0.0	0.0	0.0	0.0	0.0
	1.88/_36.90	1.86/_34.30	1.81/_28.71	1.76/_22.50	1.73/_19.10
	0.33/_-112.6	0.33/_-111.1	0.33/_-106.3	0.34/_-96.00	0.36/_-85.20
REFN	0.0	0.0	0.0	0.0	0.0
	8.91/_4.000	9.39/_-.010	10.45/_-7.64	11.61/_-14.5	12.24/_-17.9
	0.52/_-124.5	0.52/_-123.9	0.50/_-120.2	0.49/_-108.1	0.51/_-92.30

TABLE 13. Sequence components of the unbalanced line currents ($I_{0,1,2}$ puA) for variations in system loading

LINE	% Increase in System Loading				
	0	10	30	50	60
	$I_{0,1,2}$, puA				
LOAD14-LOAD13					
	0.08/_-167.9	0.08/_-161.9	0.07/_-138.2	0.12/_-108.7	0.20/_-100.0
	2.42/_26.51	2.57/_22.30	2.90/_14.60	3.27/_7.600	3.46/_4.120
	0.22/_-148.3	0.21/_-146.5	0.22/_-139.1	0.24/_-121.0	0.29/_-103.9
LOAD12-LOAD13					
	0.08/_-179.7	0.08/_-178.9	0.07/_-174.8	0.07/_-163.1	0.09/_-150.6
	1.62/_73.00	1.62/_71.30	1.60/_67.60	1.59/_63.85	1.58/_61.90
	0.16/_-151.5	0.16/_-151.2	0.16/_-149.1	0.16/_-142.8	0.16/_-134.5
HBUS3-LOAD14					
	0.048/_-177.0	0.04/_-168.4	0.03/_-122.8	0.08/_-86.10	0.15/_-83.00
	1.51/_38.10	1.57/_33.50	1.71/_24.90	1.86/_16.50	1.95/_12.21
	0.19/_-147.0	0.19/_-145.1	0.19/_-136.6	0.21/_-116.7	0.26/_-98.00
LOAD5-LOAD12					
	0.03/_169.9	0.02/_178.20	0.02/_-97.82	0.09/_-73.50	0.17/_-76.30
	2.84/_18.99	3.07/_15.60	3.56/_9.500	4.07/_4.160	4.34/_1.520
	0.19/_-153.5	0.19/_-151.7	0.19/_-143.2	0.20/_-119.9	0.25/_-97.50
LOAD13-LOAD10					
	0.076/_176.5	0.07/_175.20	0.08/_171.50	0.09/_164.90	0.10/_158.50
	1.41/_93.20	1.42/_93.50	1.45/_94.20	1.49/_94.80	1.51/_95.20
	0.10/_-153.9	0.10/_-155.3	0.10/_-160.3	0.11/_-171.4	0.13/_178.00

negligible compared to the positive sequence increases, they may become significant under different system operating conditions.

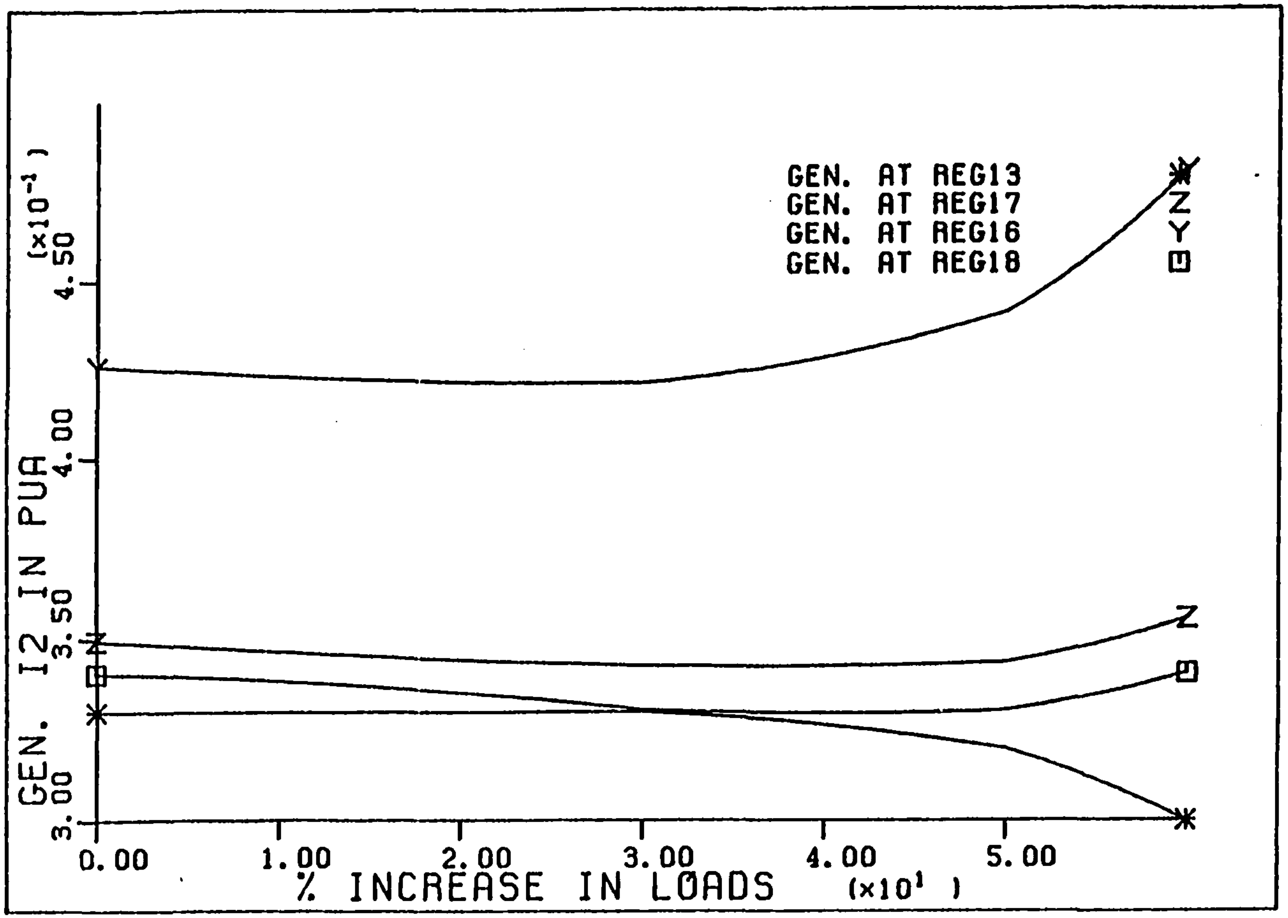

FIGURE 27. Relation between the negative sequence currents induced in the generators with variations in the system loading - part 1

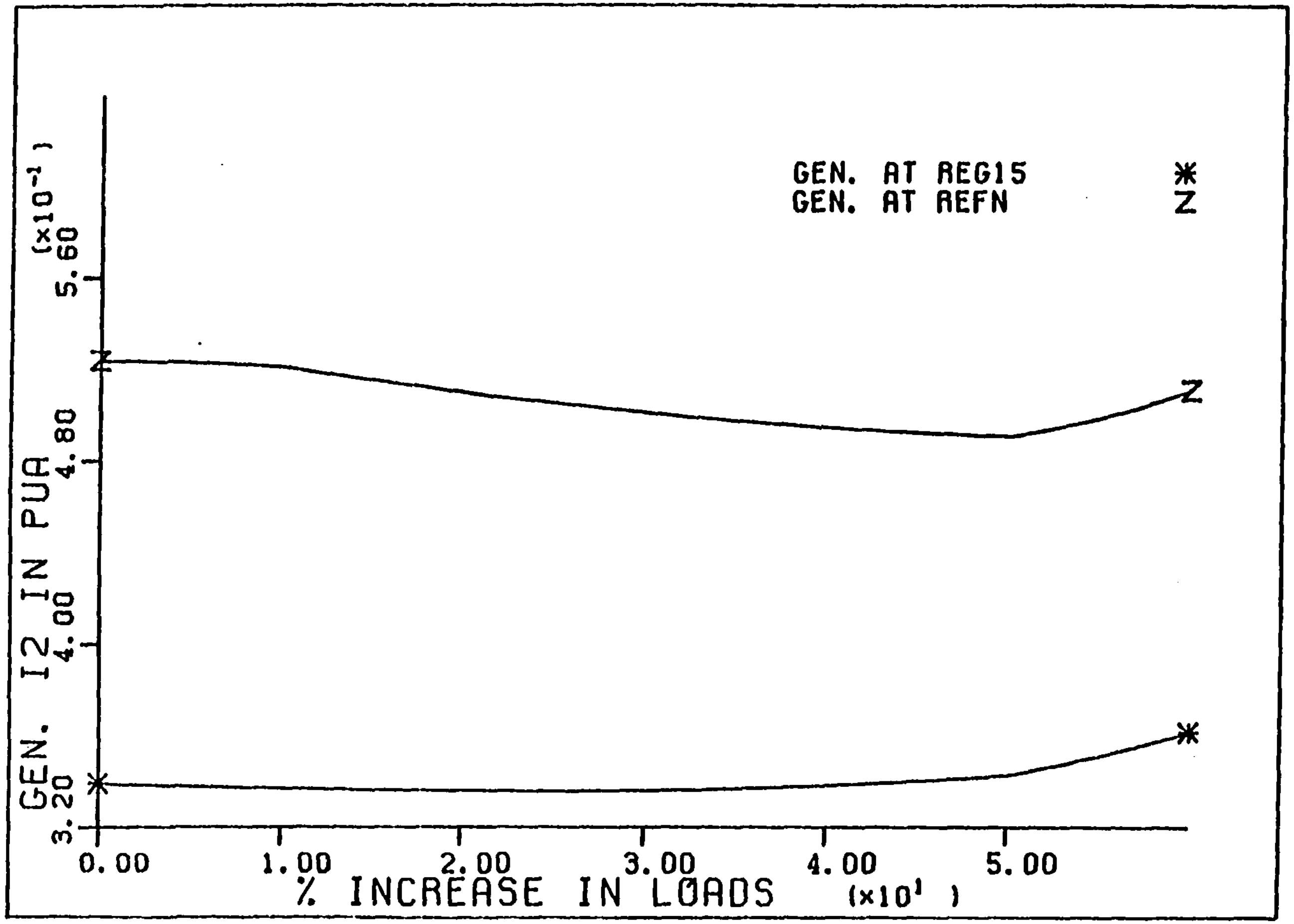

FIGURE 28. Relation between the negative-sequence currents induced in the generators with variations in the system loading - part 2

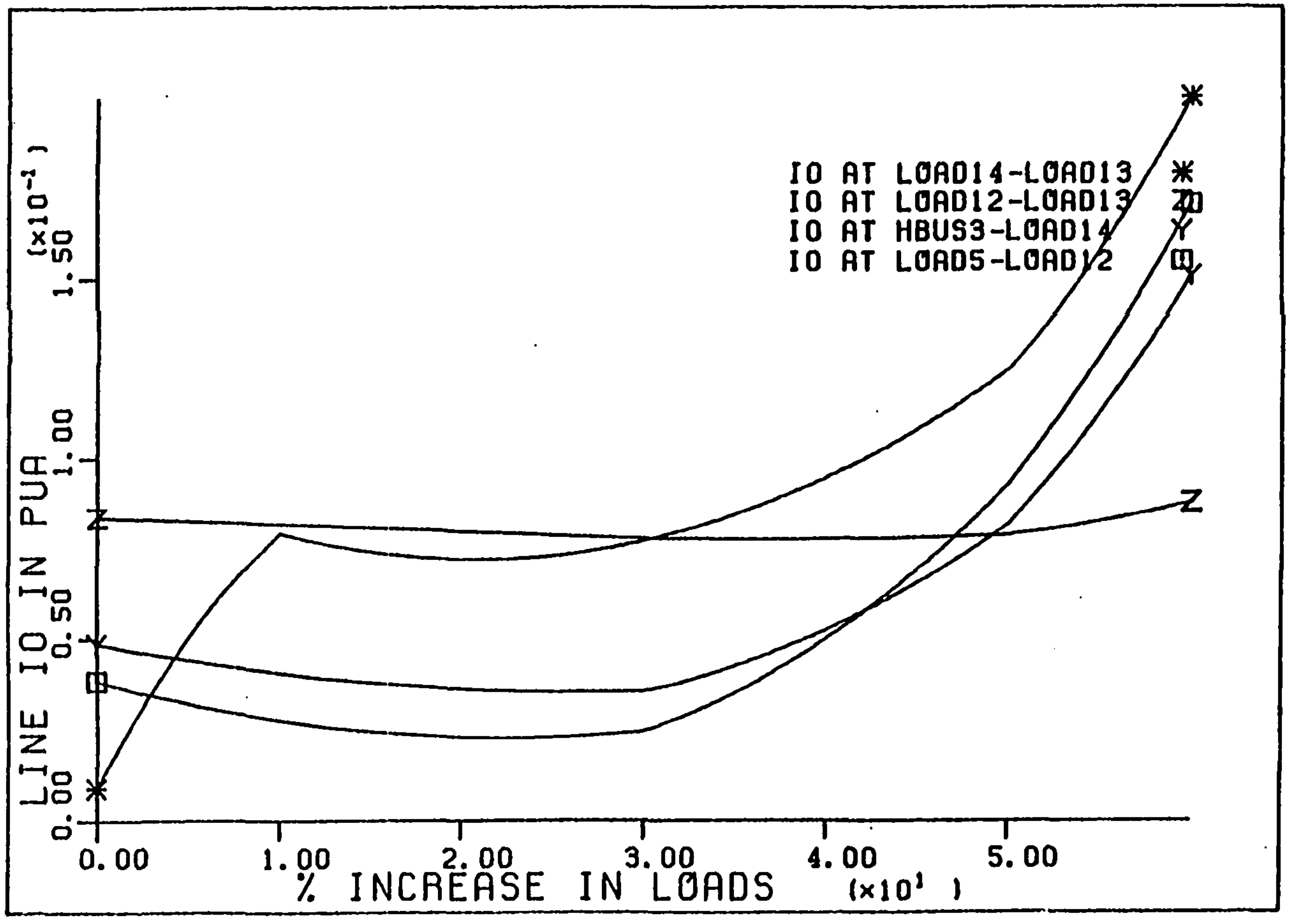

FIGURE 29. Relation between the zero-sequence component of the unbalanced line currents with variation in system loading

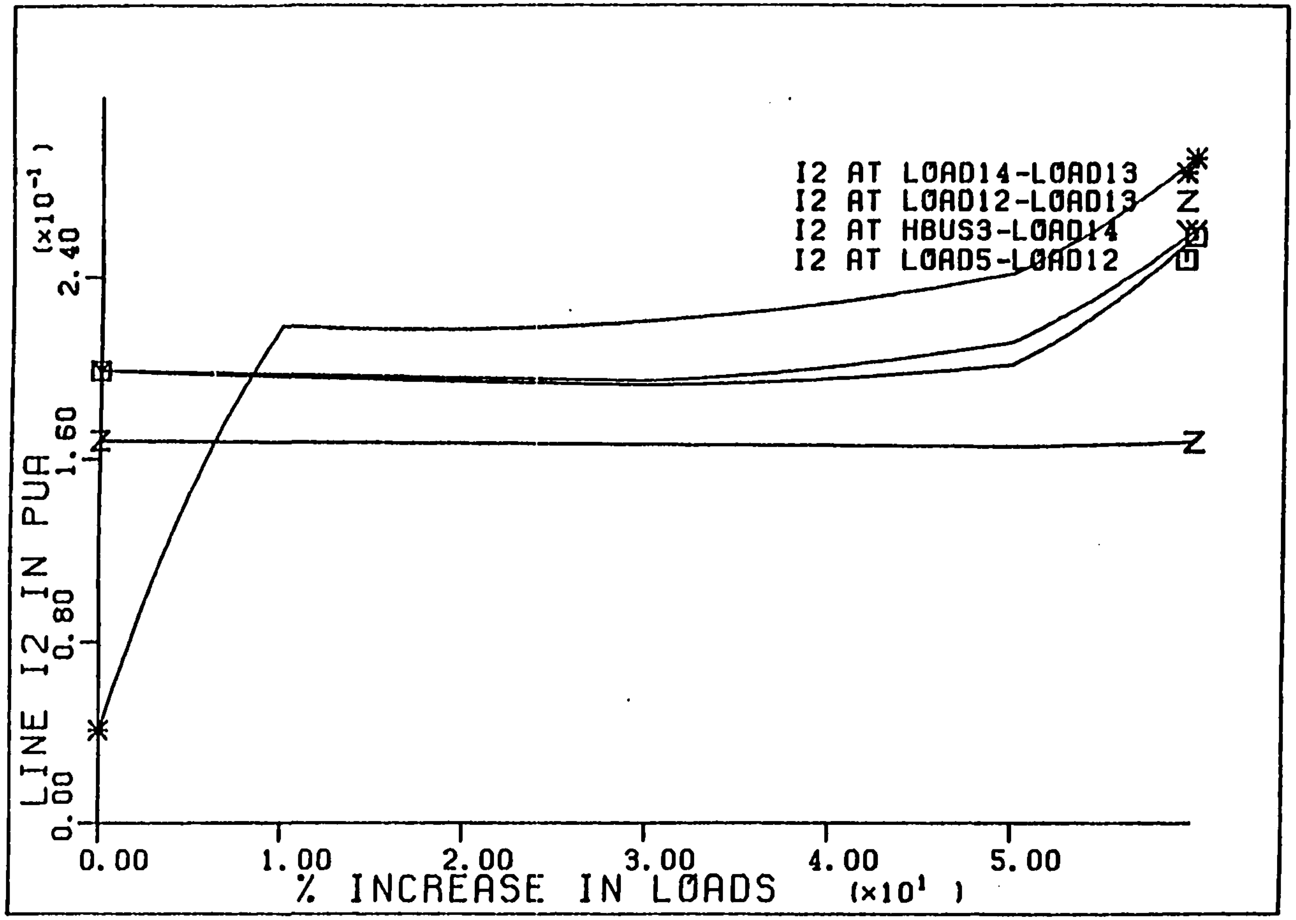

FIGURE 30. Relation between the negative-sequence component of the unbalanced line currents with variation in system loading

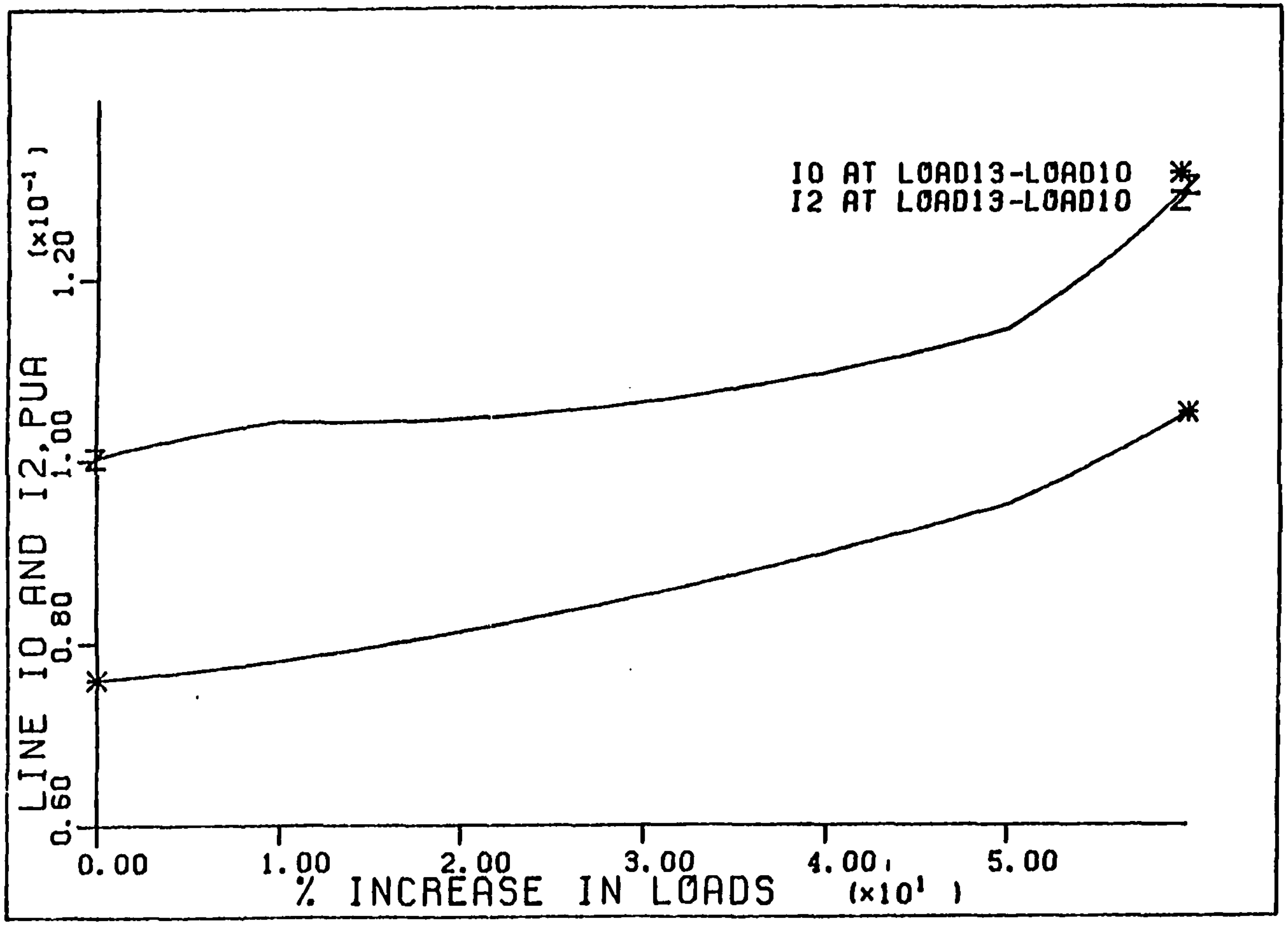

FIGURE 31. Relation between the zero-sequence and negative-sequence components of the unbalanced line currents with variations in system loading

It is clear from these results that unbalances due to untransposed lines vary rather significantly as system loading increases. This agrees with the outcome of the analyses presented in Chapter II.

3. Effect of power coupling on power flows

In order to demonstrate the effect of power coupling in an unbalanced system, two lines with the least and the most unbalanced currents are chosen and the total power at the sending end and receiving end of each phase of the line is compared. These comparisons were conducted for the first two cases considered in section B and are presented in Tables 14 and 15.

The results given in Tables 14 and 15 agree with the discussion presented in section E of Chapter II. As is shown in Table 14, for the balanced lines in a balanced system, the real power loss/phase for each line is positive and is 1/3 of the total 3-ϕ real power loss on that line; whereas, in a system with untransposed lines, the real power loss per phase is unbalanced with some negative values. However, the total real 3-ϕ power loss was shown to be positive and about the same value as in the balanced system. These are shown in Table 15.

It should be realized that the total 3-ϕ real power loss in a line in an unbalanced system is not always the same as that in a balanced system. Since real power losses increase as unbalances increase, the total 3-ϕ power loss in a line in a highly unbalanced system may be higher. To demonstrate this, the power flows in a case with both network and loads unbalanced (case 4 of section B) are shown in Table 16.

TABLE 14. Comparisons between the sending end and receiving end power flows in case 1

LINES	Sending End Power $P_{a,b,c}$	$Q_{a,b,c}$	Receiving End Power $P_{a,b,c}$	$Q_{a,b,c}$	Power Loss/Phase P_L	Q_L
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
LOAD3-LOAD10	1.258	-13.9	1.255	-3.3	0.003	-10.6
	1.258	-13.9	1.255	-3.3	0.003	-10.6
	1.258	-13.9	1.255	-3.3	0.003	-10.6

Total 3-Φ Power Loss	
$P_{L_{3\phi}}$	$Q_{L_{3\phi}}$
(MW)	(MVAR)
0.009	-31.8

LINES	$P_{a,b,c}$	$Q_{a,b,c}$	$P_{a,b,c}$	$Q_{a,b,c}$	P_L	Q_L
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
LOAD14-LOAD13	69.75	-50.1	69.49	-42.09	0.26	-8.01
	69.75	-50.1	69.49	-42.09	0.26	-8.01
	69.75	-50.1	69.49	-42.09	0.26	-8.01

Total 3-Φ Power Loss	
$P_{L_{3\phi}}$	$Q_{L_{3\phi}}$
(MW)	(MVAR)
0.78	-24.03

4. Effects of load unbalances

It was shown in the steady-state analysis (Chapter II) that unbalanced loads would contribute unbalances to the system.

In this section, the effects of unbalanced loads will be investigated and the criteria developed in Chapter II will be examined. To study the effects of unbalanced 3-ϕ loads, two different unbalanced loads are considered at LOAD13 with other loads in the system represented balanced (same t's and s's). These two loads were selected

TABLE 15. Comparisons between the sending end and receiving end power flows in case 1

LINES	Sending End Power $P_{a,b,c}$	Sending End Power $Q_{a,b,c}$	Receiving End Power $P_{a,b,c}$	Receiving End Power $Q_{a,b,c}$	Power Loss/Phase P_L	Power Loss/Phase Q_L
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
LOAD3-LOAD10	-1.24	-11.9	-0.15	-2.1	-1.09	-9.80
	0.79	-16.9	0.58	-5.6	0.21	-11.3
	4.21	-13.4	3.32	-2.53	0.89	-10.9
			Total 3-Φ Power Loss $P_{L_{3\phi}}$ (MW)	$Q_{L_{3\phi}}$ (MVAR)		
			0.010	-32.0		
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
LOAD14-LOAD13	60.30	-41.2	60.90	-33.40	-0.6	-7.80
	71.90	-56.7	71.10	-48.10	0.80	-8.60
	77.00	-53.4	76.40	-45.90	0.60	-7.50
			Total 3-Φ Power Loss $P_{L_{3\phi}}$ (MW)	$Q_{L_{3\phi}}$ (MVAR)		
			0.80	-23.90		

so that they yield the same degree of unbalances. The maximum magnitude of sequence components of the unbalanced line current (at LOAD14-LOAD13) is obtained and is shown in Table 17.

For comparison purposes, the magnitude of I_0 and I_2 obtained from (2.13) and (2.14) (unbalanced 3-ϕ load criteria), along with degree of load unbalances are also presented.

As is shown in Table 17, two different sizes of unbalanced 3-ϕ loads with the same degree of unbalances cause about the same unbalance

TABLE 16. Comparisons between the sending end and receiving end power flows in case 4

LINES	Sending End Power $P_{a,b,c}$	Sending End Power $Q_{a,b,c}$	Receiving End Power $P_{a,b,c}$	Receiving End Power $Q_{a,b,c}$	Power Loss/Phase P_L	Power Loss/Phase Q_L
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
LOAD3-LOAD10	-17.47	-32.5	-17.64	-20.7	0.17	-11.8
	20.52	-3.42	20.28	5.8	0.24	-9.22
	1.27	-2.1	1.56	7.8	-0.29	-9.9
	Total 3-Φ Power Loss					
	$P_{L_{3\phi}}$ (MW)		$Q_{L_{3\phi}}$ (MVAR)			
	0.12		-30.9			
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)
LOAD14-LOAD13	23.92	-123.6	25.17	-115.2	-1.25	-8.4
	97.21	-9.69	92.98	-4.29	4.23	-5.4
	89.03	-4.41	89.66	-4.03	-0.63	-0.38
	Total 3-Φ Power Loss					
	$P_{L_{3\phi}}$ (MW)		$Q_{L_{3\phi}}$ (MVAR)			
	2.35		-14.20			

TABLE 17. Effect of unbalanced 3-ϕ loads on system unbalances (unbalanced load at LOAD13, all other loads balanced)

LOAD MVA	Actual Values I_0	Actual Values I_2	s_1 s_2 s_3	t_1 t_2 t_3	Estimated Values I_0	Estimated Values I_2
45 + j25			25	15		
5 + j 0	0.28	0.38	-15	-10	0.45	0.42
10 + j 5			-10	-5		
75 + j25			25	15		
35 + j 0	0.31	0.40	-15	-10	0.45	0.42
40 + j 5			-10	-5		

currents in the system which are somewhat less than the estimated values. This indicates that the unbalanced 3-ϕ load criteria would give a relatively good estimate of the significance of unbalances caused by a 3-ϕ load. Interesting enough, unbalances somewhat decreased when LOAD11 was also represented unbalanced which would indicate some cancellation effects due to the principle of superposition. This is shown in Table 18.

TABLE 18. Effect of unbalanced 3-ϕ loads on system unbalances (unbalanced loads at LOAD13 and LOAD11)

LOAD MVA	Actual Values I_0	I_2	s_1 s_2 s_3	t_1 t_2 t_3	Estimated Values I_0	I_2
40 + j25 0 + j 0 5 + j 5	0.22	0.26	25 -15 -10	15 -10 -5	0.45	0.42
120 + j25 80 + j 0 85 + j 5	0.28	0.32	25 -15 -10	15 -10 -5	0.45	0.42

To examine the effects of 1-ϕ loads, 4 different types of 1-ϕ loads were considered at phase b of LOAD13 with other loads represented balanced. The maximum magnitude of sequence components of unbalanced line current (also at LOAD14-LOAD13) along with the degree of load unbalances (t's and s's) a values are shown in Table 19.

TABLE 19. Effect of 1-ϕ load on system unbalances 1-ϕ load on phase b of LOAD13, all other loads balanced

LOAD MVA	Actual Values I_0	I_2	s_1 s_2 s_3	t_1 t_2 t_3	Estimated Values I_0	I_2
30 + j 15	0.27	0.25	-10 20 -10	-5 10 -5	0.34	0.34
70 + j12	0.58	0.54	-23 46 -23	-4 8 -4	0.71	0.71
100 + j80	1.58	1.46	-33 67 -33	-27 54 -27	1.28	1.28
128 +j 9	1.10	1.10	-43 86 -43	-3 6 -3	1.29	1.29

The results clearly show that unbalances caused by a 1-ϕ load increase with the size of the load and estimated values consistently predict the maximum unbalance currents caused by the load except for a load of 100+j80 MVA. As was mentioned earlier (section D of Chapter II), the estimated values obtained from (2.19) for a large 1-ϕ load with relatively low power factor would give a pessimistic value which may not represent a good estimate. At any rate, the predicted value of 1.28, in this case, still would represent a significant unbalance that could justify the 3-ϕ analysis of the system.

5. Comparisons between the 3-ϕ load flow program and system reduction method

In this section, comparisons between the 3-ϕ load-flow program and the new system reduction method for various unbalanced conditions will be made to show the practical application of this method.

The unbalanced cases considered are as follows:

1. Unbalanced network inside of study area, balanced bus loading.
2. Balanced network, unbalanced bus loading inside of study area.

The order of node numbering presented in Chapter II has been followed here. The study area is therefore identified by nodes 1-10 (see Figure 20). The operating conditions for case 1 are similar to those given in Tables 3a and 3b. To represent case 2, the load at bus LOAD13 is represented unbalanced (see Table 20).

TABLE 20. Unbalanced bus loading at bus LOAD13

	Phase a		Phase b		Phase c	
LOAD BUS	MW	MVAR	MW	MVAR	MW	MVAR
LOAD13	20	10	130	50	140	60

Line flow information for the two lines connected to LOAD13, the double-circuit line LOAD8-LOAD9, and at the 2 generators inside of the study area are obtained and are shown in Tables 21-30.

Comparisons between the results show fairly good agreement when only the network is unbalanced. Where the load becomes highly unbalanced, the results obtained by the system reduction method would still represent a good estimate of unbalances except at the generators' terminals. This discrepancy has been expected for a highly unbalanced system, since the assumption of phase voltages being equal in magnitude would no longer be valid. At any rate, in spite of this discrepancy, the results obtained by the system reduction method indicate some significant unbalances at the generators' terminals.

D. Conclusions

Based on the analyses in Chapter II and the results obtained in this chapter, the following may be concluded:

1. Unbalances due to untransposed transmission lines increase in magnitude with an increase in the length of untransposed lines and/or an increase in the system loading.
2. It appears, from the results, that load unbalances dominate the unbalances caused by untransposed lines, mainly, on the lines in the vicinity of the unbalanced loads. Some criteria have been developed that can be used to obtain some estimates of the degree of significance of the unbalances caused by an

unbalanced load. Based on these criteria, the need for 3-ϕ representation of the system may be justified.

3. Power coupling phenomena have been thoroughly analyzed and discussed. This phenomena play an important role in unbalanced transmission systems. It is related to the differences in power flows in phases of transmission lines.
4. A non-iterative method was developed to be used as an alternative to 3-ϕ load-flow programs. This method can be used to get an estimate of the unbalances in the system. Comparisons with 3-ϕ load-flow program revealed the accuracy and the practicality of this method.

TABLE 21. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for network unbalances - Sequence voltages

LINE	3-Φ LOAD-FLOW PROGRAM $V_{0,1,2}$(puV)	SYSTEM REDUCTION METHOD $V_{0,1,2}$(puV)
LOAD14-LOAD13	0.0102/_52.4 1.0180/_-9.46 0.0195/_111.4	0.0140/_52.9 1.0160/_-9.18 0.0177/_103.4
LOAD10-LOAD13	0.0057/_79.0 1.0325/_-7.95 0.0123/_122.0	0.0084/_69.5 1.0319/_-7.85 0.0110/_114.7
LOAD8-LOAD9(1)	0.0010/_36.8 1.0363/_-0.7 0.0066/_101.3	0.0012/_44.85 1.0359/_-0.7 0.0065/_93.38
LOAD8-LOAD9(2)	0.0010/_36.8 1.0363/_-0.7 0.0066/_101.3	0.0012/_44.85 1.0359/_-0.7 0.0065/_93.38

TABLE 22. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for network unbalances - Sequence components of line currents

LINE	3-Φ LOAD-FLOW PROGRAM $I_{0,1,2}$(puA)	SYSTEM REDUCTION METHOD $I_{0,1,2}$(puA)
LOAD14-LOAD13	0.0727/_167.3 2.1940/_11.81 0.1930/_-160.3	0.0923/_154.9 2.2064/_12.21 0.1919/_-167.2
LOAD10-LOAD13	0.0786/_168.5 1.5115/_67.60 0.1860/_-165.1	0.0846/_166.7 1.4980/_68.21 0.1827/_-167.8
LOAD8-LOAD9(1)	0.0196/_128.4 1.2399/_9.79 0.0636/_175.7	0.0250/_135.9 1.2402/_10.03 0.0947/_173.9
LOAD8-LOAD9(2)	0.0297/_121.1 1.2434/_9.62 0.0720/_-175.1	0.0320/_126.6 1.2412/_9.62 0.0510/_178.0

TABLE 23. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for network unbalances - Power flows

	3-Φ LOAD-FLOW PROGRAM		SYSTEM REDUCTION METHOD	
LINE	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)
	61.5	-22.3	61.2	-23.9
LOAD14-LOAD13	71.2	-31.6	71.4	-31.0
	75.4	-27.5	76.0	-27.3
	5.0	-47.6	4.4	-47.9
LOAD10-LOAD13	15.1	-54.7	14.6	-53.7
	18.9	-49.0	18.2	-48.7
	39.5	-8.2	38.3	-8.6
LOAD8-LOAD9(1)	43.3	-9.1	43.9	-9.9
	43.5	-6.1	44.0	-5.4
	39.3	-8.1	39.8	-8.3
LOAD8-LOAD9(2)	43.0	-9.2	42.8	-8.3
	44.5	-5.9	43.9	-6.4

TABLE 24. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for network unbalances - Continuous current unbalance at the high voltage bus of the generators

GENERATOR	3-Φ LOAD-FLOW PROGRAM $I_{0,1,2}$(puA)	SYSTEM REDUCTION METHOD $I_{0,1,2}$(puA)
REG18	0.0 2.6734/_43.1 0.1604/_-168.7	0.0 2.6280/_43.5 0.1573/_-176.6
REG16	0.0 2.318/_43.8 0.262/_-170.7	0.0 2.226/_44.9 0.248/_-177.9

TABLE 25. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for network unbalances - Power at the high voltage bus of the generators

	3-Φ LOAD-FLOW PROGRAM		SYSTEM REDUCTION METHOD	
GENERATOR	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)
REG18	61.6 68.6 69.7	-62.3 -69.7 -59.9	60.2 67.6 67.6	-62.4 -68.9 -58.7
REG16	45.2 56.2 58.7	-56.7 -68.9 -53.1	42.4 53.8 54.6	-56.4 -66.4 -51.0

TABLE 26. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for load unbalances - Sequence voltages

LINE	3-Φ LOAD-FLOW PROGRAM $V_{0,1,2}$(puV)	SYSTEM REDUCTION METHOD $V_{0,1,2}$(puV)
	$0.1290\angle 19.3$	$0.0764\angle 24.7$
LOAD14-LOAD13	$1.0348\angle -9.74$	$1.0360\angle -9.52$
	$0.0992\angle 53.39$	$0.0571\angle 61.46$
	$0.0389\angle 13.2$	$0.0187\angle 36.3$
LOAD10-LOAD13	$1.0373\angle -8.16$	$1.0368\angle -7.96$
	$0.0431\angle 59.33$	$0.0220\angle 71.53$
	$0.0049\angle 23.1$	$0.0030\angle 34.57$
LOAD8-LOAD9(1)	$1.0374\angle -0.9$	$1.0369\angle -0.7$
	$0.0231\angle 59.40$	$0.0131\angle 67.78$
	$0.0049\angle 23.1$	$0.0030\angle 34.57$
LOAD8-LOAD9(2)	$1.0374\angle -0.9$	$1.0369\angle -0.7$
	$0.0231\angle 59.40$	$0.0131\angle 67.78$

TABLE 27. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for load unbalances - Sequence components of line currents

LINE	3-Φ LOAD-FLOW PROGRAM $I_{0,1,2}$(puA)	SYSTEM REDUCTION METHOD $I_{0,1,2}$(puA)
LOAD14-LOAD13	1.0475/_131.8 2.6730/_23.44 1.4417/_149.64	0.936/ 134.8 2.694/_27.10 1.2019/_155.17
LOAD10-LOAD13	0.3636/_131.2 1.6918/_67.30 0.6476/_153.70	0.2742/_136.9 1.7011/_68.28 0.4694/_162.05
LOAD8-LOAD9(1)	0.0720/_110.8 1.2510/_10.8 0.1548/_148.9	0.0410/_127.7 1.2543/_10.91 0.1239/_163.4
LOAD8-LOAD9(2)	0.0825/_110.1 1.2634/_10.2 0.1526/_158.04	0.0480/_122.5 1.2583/_10.4 0.0800/_160.9

TABLE 28. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for load unbalances - Power flows

	3-Φ LOAD-FLOW PROGRAM		SYSTEM REDUCTION METHOD	
LINE	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)
	15.9	-103.9	17.0	-91.3
LOAD14-LOAD13	103.5	-45.6	97.4	-51.9
	105.4	-28.6	106.6	-36.9
	-13.2	-76.3	-7.7	-66.8
LOAD10-LOAD13	28.4	-59.2	23.0	-60.2
	28.1	-38.4	26.6	-45.8
	37.7	-13.2	37.9	-10.6
LOAD8-LOAD9(1)	45.6	-10.3	45.2	-10.9
	43.8	- 3.2	44.3	-4.9
	37.8	-12.4	39.6	-10.1
LOAD8-LOAD9(2)	45.4	-10.3	44.1	- 9.1
	45.4	- 2.9	44.3	- 5.9

TABLE 29. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for load unbalances - Continuous current unbalance at the high voltage bus of the generators

GENERATOR	3-Φ LOAD-FLOW PROGRAM $I_{0,1,2}$(puA)	SYSTEM REDUCTION METHOD $I_{0,1,2}$(puA)
REG18	0.0 2.7108/_43.8 0.5620/_149.40	0.0 2.6860/_43.8 0.3191/_157.80
REG16	0.0 2.4610/_46.7 1.0670/_147.00	0.0 2.4260/_46.6 0.6300/_154.50

TABLE 30. Comparisons between the solutions of the 3-ϕ load-flow program and the system reduction method for load unbalances - Power at the high voltage bus of the generators

	3-Φ LOAD-FLOW PROGRAM		SYSTEM REDUCTION METHOD	
GENERATOR	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)	$P_{a,b,c}$(MW)	$Q_{a,b,c}$(MVAR)
REG18	52.1 82.8 65.0	-75.6 -77.6 -45.7	57.2 74.6 66.7	-68.9 -73.0 -53.8
REG16	25.3 83.2 51.6	-85.7 -89.1 -29.0	35.4 69.1 54.5	-73.0 -80.4 -43.3

IV. TRANSIENT ANALYSIS OF UNBALANCED THREE-PHASE TRANSMISSION SYSTEM

A. Introduction

When a traveling wave on a line reaches a transition point at which there is an abrupt change of circuit constants, as an open or short circuited terminal or a junction with another line, a part of the wave is reflected back on the line, and a part may pass on to other sections of the circuit. At the transition point itself, the voltage (or current) may be anything from zero to double the magnitude of the wave, depending on the terminal characteristics [30].

The intent of this chapter is to demonstrate the dependence of traveling wave equations on the unbalanced elements, namely, unbalanced load and untransposed transmission lines, that may exist at the transition point. Transmission lines will be represented by their self-series impedances and mutually coupled surge admittances. The surge admittance matrix of the line may be obtained by inverting the surge impedance matrix (see Appendix I, section 2.b). The a,b,c frame of reference is used in this chapter to represent the matrices.

B. Transition Point on Three-Phase Systems

Consider a transition point as shown in Figure 32. It consists of a junction at which there is a load (assumed to be inductive) represented by admittances to ground (see Figure 33 and Appendix I) and two trans-

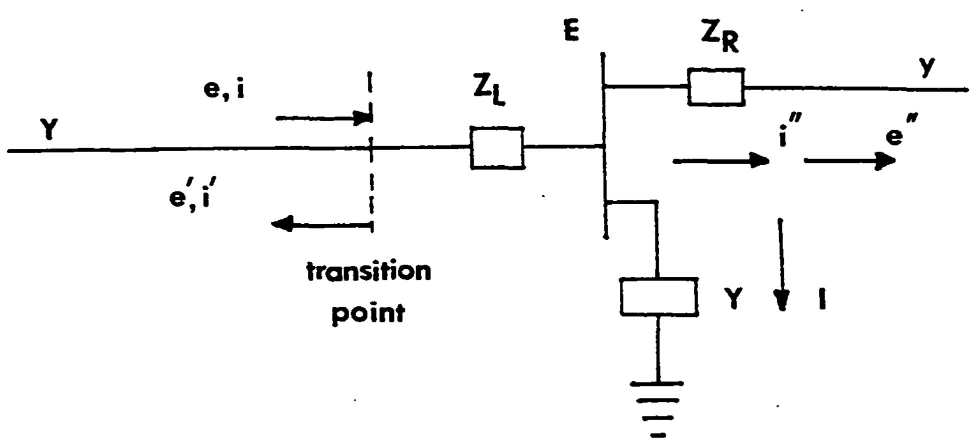

FIGURE 32. A transition point

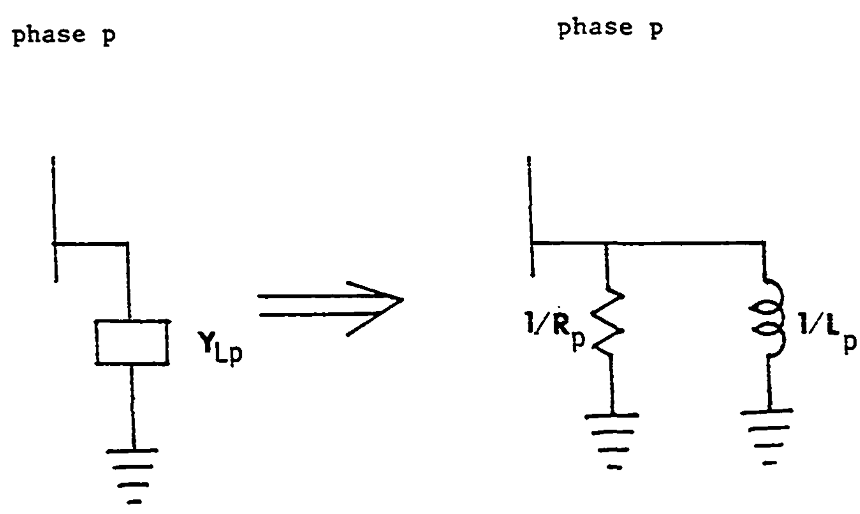

FIGURE 33. Load equivalent resistance and inductance

mission lines of surge admittance matrices Y and y joined through series impedances Z_L and Z_R, respectively.

Let

e,i = potential and current incident waves

e',i' = potential and current reflected waves

e",i" = potential and current transmitted waves

The directions of these waves are shown in Figure 32. It will also be convenient to introduce the notations

$Z_{Lp} = R_{Lp} + SL_{Lp}$

$Z_{Rp} = R_{Rp} + SL_{Rp}$

$Y_{Lp} = 1/R_p - S/L_p$

$S = j\omega$

$p = 1,2,3$

where

1 corresponds to phase a

2 corresponds to phase b

3 corresponds to phase c

The total current and voltage at the transition point on any incoming phase p is the sum of the incident and reflected waves on that phase. It can be shown [30] that the total current at the transition point is

$$i_p + i_p' = Y_{p1}(e_1-e_1') + Y_{p2}(e_2-e_2') + Y_{p3}(e_3-e'_3) \tag{4.1}$$

The potential across the admittance Y_L is

$$E_p = (e_p+e_p') - R_{Lp}(i_p+i_p') - L_{Lp}d/d_t(i_p+i_p') \tag{4.2}$$

and the current through Y_L, therefore, is

$$I_p = E_p/R_p + 1/L_p\int E_p dt \tag{4.3}$$

The current transmitted to the outgoing line is

$$i_p'' = y_{p1}e_1'' + y_{p2}\, e_2'' + y_{p3}e_3'' \tag{4.4}$$

The condition of current continuity requires that

$$i_p + i_p' = i_p'' + I_p \tag{4.5}$$

The potential wave transmitted to the outgoing line is

$$e_p'' = E_p - R_{Rp}i_p'' - L_{Rp}di_p''/dt \tag{4.6}$$

Differentiating Eq. 4.3 with respect to t and substituting Eqs. 4.1 and 4.2 yields

$$\begin{aligned} dI_p/dt = {} & (1/R_p)[(d/dt)(e_p+e_p') - R_{Lp}Y_{p1}(d/dt)(e_1-e_1') - \\ & R_{Lp}Y_{p2}(d/dt)(e_2-e_2') - R_{Lp}Y_{p3}(d/dt)(e_3-e_3') - \\ & L_{Lp}Y_{p1}(d^2/dt^2)(e_1-e_1') - L_{Lp}Y_{p2}(d^2/dt^2)(e_2-e_2') - \\ & L_{Lp}Y_{p3}(d^2/dt^2)(e_3-e_3')] + (1/Lp)[(e_p+e_p') - \\ & Y_{p1}R_{Lp}(e_1-e_1') - R_{Lp}Y_{p2}(e_2-e_2') - Y_{p3}R_{Lp}(e_3-e_3') - \\ & L_{Lp}Y_{p1}(d/dt)(e_1-e_1') - L_{Lp}Y_{p2}(d/dt)(e_2-e_2') - \\ & L_{Lp}Y_{p3}(d/dt)(e_3-e_3')] \end{aligned} \tag{4.7}$$

Differentiating Eq. 4.5 with respect to t and substituting Eqs. 4.1, 4.4 and 4.7 gives

$$\begin{aligned} & Y_{p1}(d/dt)(e_1-e_1') + Y_{p2}(d/dt)(e_2-e_2') + Y_{p3}d/dt(e_3-e_3') = \\ & y_{p1}(d/e_1''/dt) + y_{p2}(de_2''/dt) + y_{p3}\ (de_3''/dt) + \\ & (1/Rp)[d/dt(e_p+e_p') - R_{Lp}Y_{p1}(d/dt)(e_1-e_1') - \\ & R_{Lp}Y_{p2}(d/dt)(e_2-e_2') - R_{Lp}Y_{p3}(d/dt)(e_3-e_3') - \\ & L_{Lp}Y_{p1}(d^2/dt^2)(e_1-e_1') - L_{Lp}Y_{p2}(d^2/dt^2)(e_2-e_2') - \\ & L_{Lp}Y_{p3}(d^2/dt^2)(e_3-e_3')] + (1/Lp)[(e_p+e_p')-Y_{p1}R_{Lp}(e_1-e_1')- \\ & Y_{p2}R_{Lp}(e_2-e_2')-Y_{p3}R_{Lp}(e_3-e_3')-L_{Lp}Y_{p1}(d/dt)(e_1-e_1')- \end{aligned}$$

$$L_{Lp}Y_{p2}(d/dt)(e_2-e_2')-L_{Lp}Y_{p3}(d/dt)(e_3-e_3')] \quad (4.8)$$

Differentiating Eq. 4.6 with respect to t and substituting for E_p and i_p'' from Eqs. 4.2 and 4.4 yields

$$\begin{aligned} de_p''/dt = {} & (d/dt)(e_p+e_p') - R_{Lp}Y_{p1}(d/dt)(e_1-e_1') - \\ & R_{Lp}Y_{p2}(d/dt)(e_2-e_2') - R_{Lp}Y_{p3}(d/dt)(e_3-e_3') - \\ & L_{Lp}Y_{p1}(d^2/dt^2)(e_1-e_1') - L_{Lp}Y_{p2}(d^2/dt^2)(e_2-e_2') - \\ & L_{Lp}Y_{p3}(d^2/dt^2(e_3-e_3') - R_{Rp}y_{p1}(d/dt)e_1'' - \\ & R_{Rp}y_{p2}(de_2''/dt) - R_{Rp}y_{p3}(de_3''/dt) - L_{Rp}y_{p1}(d^2e_1''/dt^2) - \\ & L_{Rp}y_{p2}(d^2e_2''/dt^2) - L_{Rp}y_{p3}(d^2e_3''/dt^2) \end{aligned} \quad (4.9)$$

Rearranging Eq. 4.8 will give

$$\begin{aligned} & ((R_{Lp}/Rp)+1+(L_{Lp}/Lp))Yp1\ (de_1'/dt)+(1/Rp)(dep'/dt) + \\ & ((R_{Lp}/Rp)+1+(L_{Lp}/Lp))Y_{p2}(de_2'/dt) + ((R_{Lp}/R_p)+L_{Lp}/L_p)+Y_{p3} \\ & (de_3'/dt)+y_{p1}(de_1''/dt)+y_{p2}(de_2''/dt) + y_{p3}(de_3''/dt)+(L_{Lp}/Rp)Y_{p1} \\ & (d^2e_1'/dt^2)+(L_{Lp}/Rp)Y_{p2}(d^2e_2'/dt^2) + (L_{Lp}/Rp)Y_{p3}(d^2e_3'/dt^2) + \\ & (R_{Lp}/Lp)Y_{p1}e_1'+(e_p'/Lp) + (R_{Lp}/Lp)Y_{p2}e_2' + (R_{Lp}/Lp)Y_{p3}e_3' = \\ & (R_{Lp}/Lp)Y_{p1}e_1-(ep/Lp) + (R_{Lp}/Lp)Y_{p2}e_2 + (R_{Lp}/Lp)Y_{p3}e_3 + \\ & ((R_{Lp}/R_p)+1+(L_{Lp}/Lp))Y_{p1}(de_1/dt)-(1/Rp)(de_p/dt) + \\ & ((R_{Lp}/Rp)+1+(L_{Lp}/Lp))Y_{p2}(de_2/dt) + ((R_{Lp}/Rp) + (L_{Lp}/Lp)+1)Y_{p3} \\ & (de_3/dt) + L_{Lp}Y_{p1}(d^2e_1/dt^2) + L_{Lp}Y_{p2}(d^2e_2/dt^2) + L_{Lp}Y_{p3}(d^2e_3/dt^2) \end{aligned} \quad (4.10)$$

Rearranging Eq. 4.9 will give

$$\begin{aligned} & R_{Lp}Y_{p1}(de_1'/dt) + (de_p'/dt) + R_{Lp}Y_{p2}(de_2'/dt) + \\ & R_{Lp}Y_{p3}(de_3'/dt) - R_{Rp}y_{p1}(de_1''/dt) - R_{Rp}y_{p2}(de_2''/dt) - \\ & R_{Rp}y_{p3}(de_3''/dt) - (de_p''/dt) + L_{Lp}Y_{p1}(d^2e_1'/dt^2) + \\ & L_{Lp}Y_{p2}(d^2e_2'/dt^2) + L_{Lp}Y_{p3}(d^2e_3'/dt^2) - L_{Rp}y_{p1}(d^2e_1''/dt^2) - \end{aligned}$$

$$L_{Rp}y_{p2}(d^2e_2''/dt^2) - L_{Rp}y_{p3}(d^2e_3''/dt^2) = -(de_p/dt) +$$

$$R_{Lp}Y_{p1}(de_1/dt) + R_{Lp}Y_{p2}(de_2/dt) + R_{Lp}Y_{p3}(de_3/dt) +$$

$$L_{Lp}Y_{p1}(d^2e_1/dt^2) + L_{Lp}Y_{p2}(d^2e_2/dt^2) + L_{Lp}Y_{p3}(d^2e_3/dt^2) \tag{4.11}$$

Now, let

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{bmatrix} \quad \begin{bmatrix} e_1' \\ e_2' \\ e_3' \\ e_1'' \\ e_2'' \\ e_3'' \\ \dot{e}_1' \\ \dot{e}_2' \\ \dot{e}_3' \\ \dot{e}_1'' \\ \dot{e}2'' \\ \dot{e}_3'' \end{bmatrix}$$

where

$$\begin{bmatrix} x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{bmatrix} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix}$$

Writing Eqs. 4.10 and 4.11 in matrix form using the state variables follows:

$$A\dot{x} + Bx = u \tag{4.12}$$

Assume matrices A and B consist of four submatrices, that is,

$$A = \left[\begin{array}{c|c} \begin{matrix} A1 \\ 3x3 \end{matrix} & \begin{matrix} A2 \\ 3x9 \end{matrix} \\ \hline \begin{matrix} A3 \\ 9x3 \end{matrix} & \begin{matrix} A4 \\ 9x9 \end{matrix} \end{array}\right]$$

and

$$B = \left[\begin{array}{c|c} \begin{matrix} B1 \\ 3x3 \end{matrix} & \begin{matrix} B2 \\ 3x9 \end{matrix} \\ \hline \begin{matrix} B3 \\ 9x3 \end{matrix} & \begin{matrix} B4 \\ 9x9 \end{matrix} \end{array}\right]$$

$$A1 = \begin{bmatrix} 1/R1 + A11^1 & A12^1 & A13^1 \\ A21^1 & A22^1 + 1/R2 & A23^1 \\ A31^1 & A32^1 & A33^1 + 1/R3 \end{bmatrix}$$

$$A2 = \begin{bmatrix} y_{11} & y_{12} & y_{13} & A11^2 & A12^2 & A13^2 & 0 & 0 & 0 \\ y_{21} & y_{22} & y_{23} & A21^2 & A22^2 & A23^2 & 0 & 0 & 0 \\ y_{31} & y_{32} & y_{33} & A31^2 & A32^2 & A33^2 & 0 & 0 & 0 \end{bmatrix}$$

$$A3 = \begin{bmatrix} 1+R_{L1}Y_{11} & R_{L1}Y_{12} & R_{L1}Y_{13} \\ R_{L2}Y_{21} & 1+R_{L2}Y_{22} & R_{L2}Y_{23} \\ R_{L3}Y_{31} & R_{L3}Y_{32} & 1+R_{L3}Y_{33} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

See Figure 34 for submatrix A4, and Figure 35 for u(t).

$$B1 = \begin{bmatrix} A11^3 + 1/L_1 & A12^3 & A13^3 \\ A21^3 & A22^3 + 1/L_2 & A23^3 \\ A31^3 & A32^3 & A33^3 + 1/L_3 \end{bmatrix}$$

$$B2 = [\ \underline{0}\ ]$$

$$B3 = [\ \underline{0}\ ]$$

$$
A4 = \begin{bmatrix}
-1-R_{R1}y_{11} & -R_{R1}y_{12} & -R_{R1}y_{13} & Y_{11}L_{L1} & Y_{12}L_{L1} & Y_{13}L_{L1} & -L_{R1}y_{11} & -L_{R1}y_{12} & -L_{R1}y_{13} \\
-R_{R2}y_{21} & -1-R_{R2}y_{22} & -R_{R2}y_{23} & Y_{21}L_{L2} & Y_{22}L_{L2} & Y_{23}L_{L2} & -L_{R2}y_{21} & -L_{R2}y_{22} & -L_{R2}y_{23} \\
-R_{R3}y_{31} & -R_{R3}y_{32} & -R_{R3}y_{33}-1 & Y_{31}L_{L3} & Y_{32}L_{L3} & Y_{33}L_{L3} & -L_{R3}y_{31} & -L_{R3}y_{32} & -L_{R3}y_{33} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

FIGURE 34. Submatrix A4

$$
u(t) = \begin{bmatrix}
\left(\frac{R_{L1}}{L_1} Y_{11} - \frac{1}{L_1}\right) e_1 + \frac{R_{L1}}{L_1} Y_{12} e_2 + \frac{R_{L1}}{L_1} Y_{13} e_3 + \left(A_{11}^{1} - \frac{1}{R_1}\right)\frac{de_1}{dt} + A_{12}^{1} \frac{de_2}{dt} + A_{13}^{1} \frac{de_3}{dt} + L_{L1} Y_{11} \frac{d^2e_1}{dt^2} + L_{L1} Y_{12} \frac{d^2e_2}{dt^2} + L_{L1} Y_{13} \frac{d^2e_3}{dt^2} \\
\frac{R_{L2}}{L_2} Y_{21} e_1 + \left(\frac{R_{L2}}{L_2} Y_{22} - \frac{1}{L_2}\right) e_2 + \frac{R_{L2}}{L_2} Y_{23} e_3 + A_{21}^{1} \frac{de_1}{dt} + \left(A_{22}^{1} - \frac{1}{R_2}\right)\frac{de_2}{dt} + A_{23} \frac{de_3}{dt} + L_{L2} Y_{21} \frac{d^2e_1}{dt^2} + L_{L2} Y_{22} \frac{d^2e_2}{dt^2} + L_{L2} Y_{23} \frac{d^2e_3}{dt^2} \\
\frac{R_{L3}}{L_3} Y_{31} e_1 + \frac{R_{L3}}{L_3} Y_{32} e_2 + \left(\frac{R_{L3}}{L_3} Y_{33} - \frac{1}{L_3}\right) e_3 + A_{31}^{1} \frac{de_1}{dt} + A_{32}^{1} \frac{de_2}{dt} \left(A_{33}^{1} - \frac{1}{R_3}\right)\frac{de_3}{dt} + L_{L3} Y_{31} \frac{d^2e_1}{dt^2} + L_{L3} Y_{32} \frac{d^2e_2}{dt^2} + L_{L3} Y_{33} \frac{d^2e_3}{dt^2} \\
\left(R_{L1} y_{11} - 1\right) \frac{de_1}{dt} + R_{L1} y_{12} \frac{de_2}{dt} + R_{L1} y_{13} \frac{de_3}{dt} + L_{L1} y_{11} \frac{d^2e_1}{dt^2} + L_{L1} y_{12} \frac{d^2e_2}{dt^2} + L_{L1} y_{13} \frac{d^2e_3}{dt^2} \\
R_{L2} y_{21} \frac{de_1}{dt} + (R_{L2} y_{22} - 1) \frac{de_2}{dt} + R_{L2} y_{23} \frac{de_3}{dt} + L_{L2} y_{21} \frac{d^2e_1}{dt^2} + L_{L2} y_{22} \frac{d^2e_2}{dt^2} + L_{L2} y_{23} \frac{d^2e_3}{dt^2} \\
R_{L3} y_{31} \frac{de_1}{dt} + R_{L3} y_{32} \frac{de_2}{dt} + (R_{L3} y_{33} - 1) \frac{de_3}{dt} + L_{L3} y_{31} \frac{d^2e_1}{dt^2} + L_{L3} y_{32} \frac{d^2e_2}{dt^2} + L_{L3} y_{33} \frac{d^2e_3}{dt^2} \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
$$

FIGURE 35. Matrix u(t)

$$B4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where

$$Aij^1 = Yij\ (1 + R_{Li}/R_i + L_{Li}/L_i) \tag{4.13}$$

$$Aij^2 = Yij\ (L_{Li}/R_i) \tag{4.14}$$

$$Aij^3 = Yij\ (R_{Li}/L_i) \tag{4.15}$$

$i,j = 1,2,3$

Examining matrices A, B, and u shows the dependence of traveling waves on equivalent load impedances and the lines' surge admittances, as well as their series impedances.

In general, the surge admittance matrix and self-series impedances of unbalanced line have the form

$$y^u = \begin{bmatrix} y_{s1} & y_{m1} & y_{m2} \\ y_{m1} & y_{s2} & y_{m3} \\ y_{m2} & y_{m3} & y_{s3} \end{bmatrix} \tag{4.16}$$

$$Zp^u = Rp^u + SLp^u \qquad p=1,2,3 \tag{4.17}$$

Equations 4.16 and 4.17, for balanced lines, have the forms

$$y^B = \begin{bmatrix} y_s & y_m & y_m \\ y_m & y_s & y_m \\ y_m & y_m & y_s \end{bmatrix} \tag{4.18}$$

$$Zp^B = R^B + sL^B \qquad p=1,2,3 \tag{4.19}$$

where

$$y_s = \frac{y_{s1} + y_{s2} + y_{s3}}{3}$$

$$y_m = \frac{y_{m1} + y_{m2} + y_{m3}}{3}$$

C. Summary and Discussion

The purpose of this analysis was to show the dependence of the coefficients of the traveling wave equations on the unbalanced elements at the transition point. The model used in this analysis did not include the overall effect of the transmission network and the load. Solving the equations obtained, therefore, would not represent the actual situation. Thus, no solution has been attempted.

From this analysis, however, untransposed transmission lines represented by Eqs. 4.18 and 4.19 would appear to give, approximately, the same solution as if the lines were represented untransposed (see Eqs. 4.16 and 4.17). This agrees with the findings of others [10,21].

Inspecting the matrices A1, B1, and u would suggest that the elements of these matrices depend on load equivalent impedances (R, L) (see Eqs. 4.13-4.15). Equivalent impedances of small loads are relatively large compared to the lines' series impedances and, since they appear as 1/R and 1/L in the equations, small loads (about 30 MVA or less in a 345 kV system) as well as their unbalances may be ignored in the analysis. Minor variations in the equivalent R and L in each phase of larger loads do not appear to affect the solution of wave equations significantly. This corresponds to minor unbalances in three-phase loads. In loads with significant unbalances, equivalent impedances vary considerably from phase to phase and this would lead to significant differences in the elements of matrices A1, B1, and u. The solutions obtained with loads represented unbalanced, therefore, would not be the same as if they were represented balanced. This may suggest that load unbalances should be considered in load representations.

The fact that the variations in the magnitude of phase voltages due to unbalances are not very significant would suggest that an equivalent impedance for each phase of unbalanced loads may be determined using the magnitude of balanced phase voltages. Unbalanced loads represented in this manner, would represent a good approximation and the solution obtained with this representation would then be reasonably accurate.

While this chapter dealt with the analytical aspect of traveling wave phenomena and their dependence on unbalances, the actual network transient solutions under different unbalance conditions will be presented in the next chapter. These results will be complementary to the material presented in this chapter, since the overall effect of network, loads, and their unbalances will all be included in the study.

V. RESULTS OF THE ELECTROMAGNETIC TRANSIENT ANALYSIS

A. Introduction

In order to illustrate the impact of the overall transmission system and its unbalances on the network transients, the electromagnetic transients of the EHV test system (see Figure 20) will be obtained and studied. Specifically, the effects of untransposed transmission lines and unbalanced loads on the transient overvoltages due to fault surges will be demonstrated.

In addition, the accuracy of using a balanced initial condition assumption will be evaluated.

The electromagnetic transients will be obtained by using the EMTP, the Electromagnetic Transients Program [33].

B. Study of the 24-Bus EHV Test System

The electromagnetic transients of the test system in the following cases were obtained and studied:

Case 1. The system is represented unbalanced using unbalanced initial conditions. The types of unbalances considered are:

1a. Untransposed lines, balanced loads.

1b. Untransposed lines, unbalanced loads.[1]

1c. Transposed lines, unbalanced loads.

----

[1] See Table 4.

Case 2. The system is represented balanced using balanced initial conditions.

Case 3. The system is represented unbalanced using balanced initial conditions. Types of unbalances considered are similar to those of case 1.

The transient analysis mainly is focused on the transient overvoltages due to clearing a single-line to ground (SLG) fault by means of single pole switching. For this purpose, a SLG fault was placed on phase b on the line side of bus LOAD10 and cleared in 3 cycles by opening phase b of line LOAD10-LOAD11. The voltage transients of 3 buses (with the most significant overvoltages) were obtained and are shown in Figures 36-56. Comparisons between the maximum transient overvoltage factors (OVF)[1] are shown in Table 31.

Transient overvoltages depend -- to some extent -- on the relative phase when the fault and switching begin. In order to take this fact into consideration, the SLG fault was placed at t=0.006 S and cleared at t=0.056 S in all cases considered.

1. Effects of untransposed transmission lines and unbalanced loads on the transient overvoltages

The impact of untransposed lines on the transient overvoltages can be observed by the comparisons between cases 1a and 2 shown in Table 31 and Figures 36-38 and 45-47. These comparisons indicate that

----

[1] The overvoltage factor is the maximum crest value of a switching surge divided by the crest value of normal line-to-ground voltage.

approximating untransposed transmission lines with transposed lines would give a rather good estimate of the transient overvoltages occurring in the system.

Examining cases 1c and 2, Figures 42-44, and 45-47 reveals that ignoring the load unbalances in network transient studies would result in an incorrect estimate (underestimate or overestimate) of the transient overvoltages. This, however, as was mentioned in Chapter IV, depends on the degree of load unbalances. Thus, to avoid this problem, it would be advisable to consider any load unbalances in network transient studies by representing all unbalanced loads as unbalanced.

2. Evaluation of the accuracy of using balanced initial conditions

Comparisons between cases 1a and 3a, 1b and 3b, 1c and 3c shown in Table 31 and Figures 36-38 and 48-50, 39-41 and 51-53, 42-44 and 54-56 show no significant differences. This indicates that utilization of balanced initial conditions in network representation, regardless of the degree of system unbalances, would lead to a reasonably accurate transient solution.

C. Conclusions

The final results of the transient analysis may be summarized as follows:

1. Untransposed transmission lines have no significant impact on transient overvoltages due to fault surges.

2. Load unbalances can affect the transients and therefore should be considered in network transient studies. This, however, depends on the degree of imbalance at the load.
3. No significant error was observed when balanced initial conditions were used in network representation.

TABLE 31. Maximum transient overvoltage factors (OVF) due to fault clearing

BUS NAME	CASE 2	CASE 1a	CASE 3a	CASE 1b	CASE 3b	CASE 1c	CASE 3c
LOAD10A	1.37	1.31	1.32	1.42	1.36	1.49	1.42
LOAD10B	1.20	1.22	1.21	1.13	1.18	1.12	1.17
LOAD10C	1.26	1.29	1.29	1.24	1.27	1.20	1.25
LOAD11A	1.27	1.23	1.24	1.35	1.30	1.38	1.32
LOAD11B	1.20	1.20	1.20	0.98	1.00	0.98	1.07
LOAD11C	1.19	1.21	1.21	1.17	1.21	1.15	1.19
LOAD13A	1.19	1.13	1.16	1.41	1.30	1.46	1.34
LOAD13B	1.18	1.18	1.15	0.94	1.06	0.95	1.10
LOAD13C	1.13	1.14	1.14	1.00	1.07	0.97	1.06

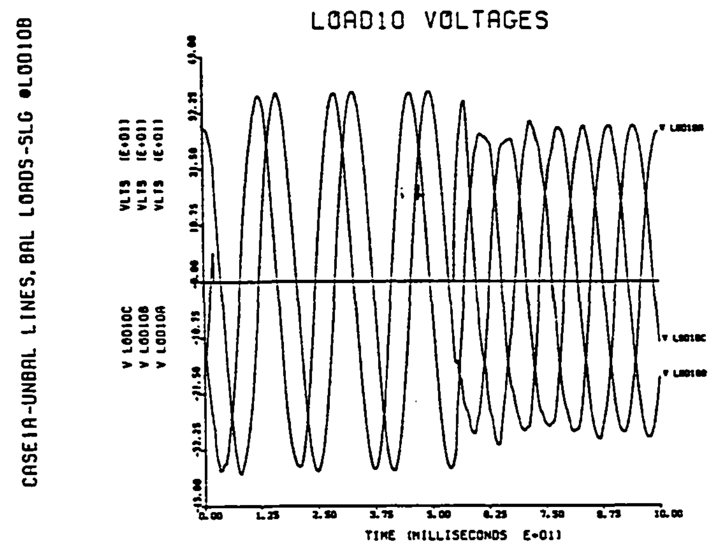

FIGURE 36. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1a).

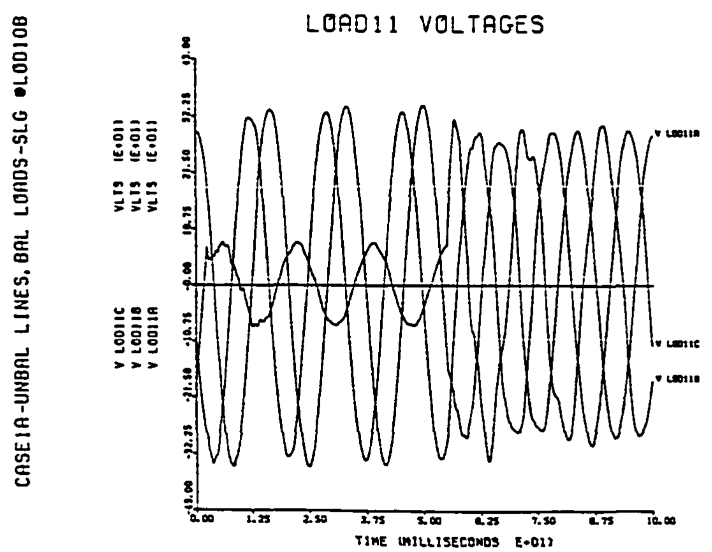

FIGURE 37. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1a)

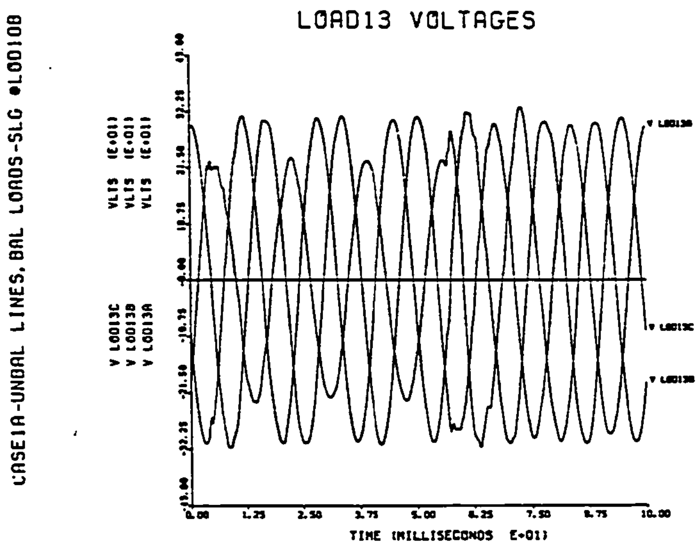

FIGURE 38. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1a)

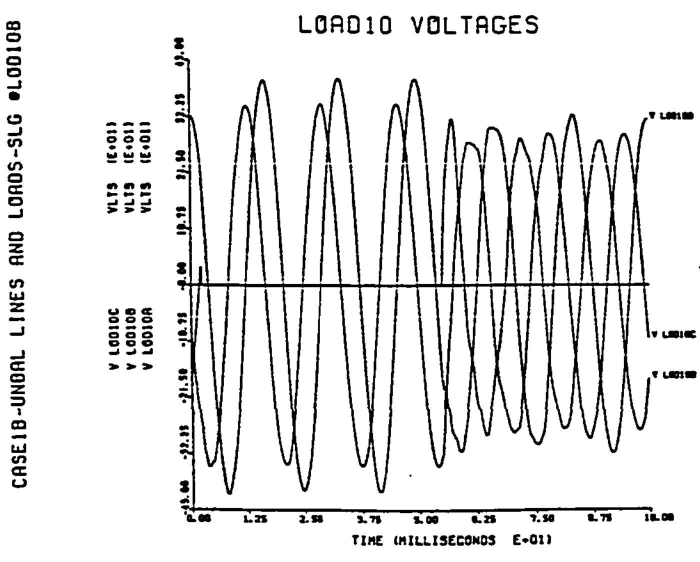

FIGURE 39. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1b)

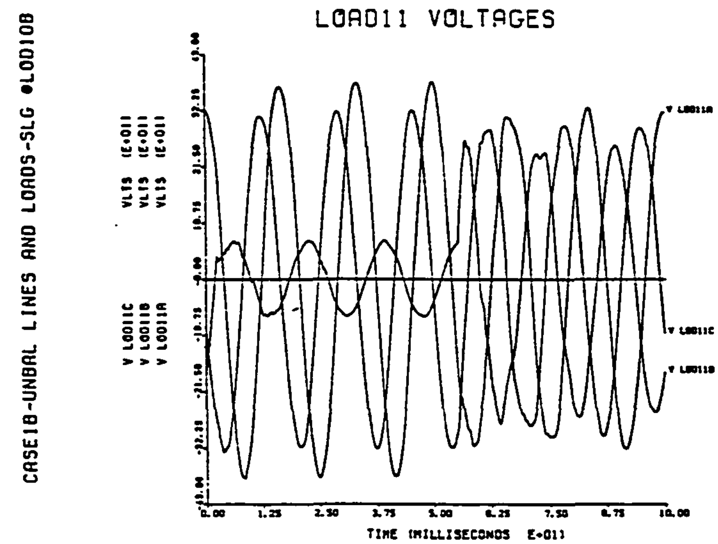

FIGURE 40. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1b)

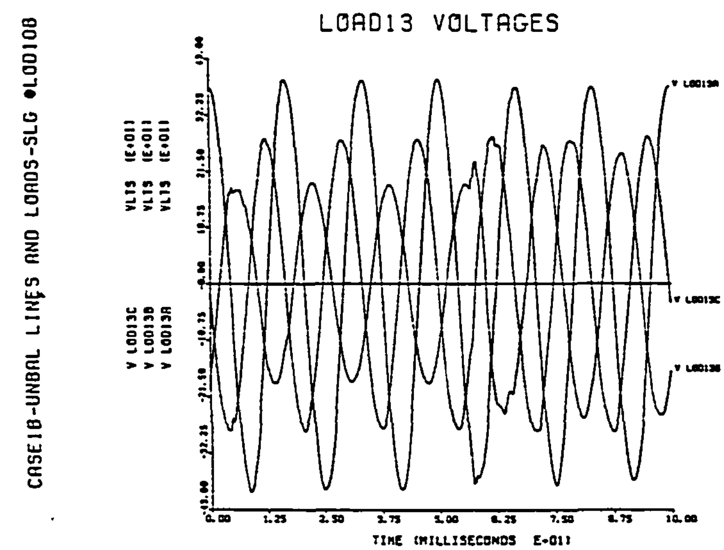

FIGURE 41. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1b)

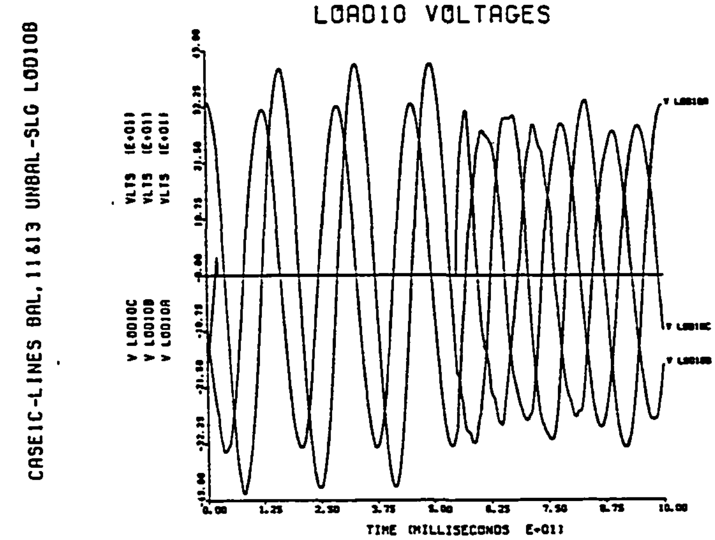

FIGURE 42. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1c)

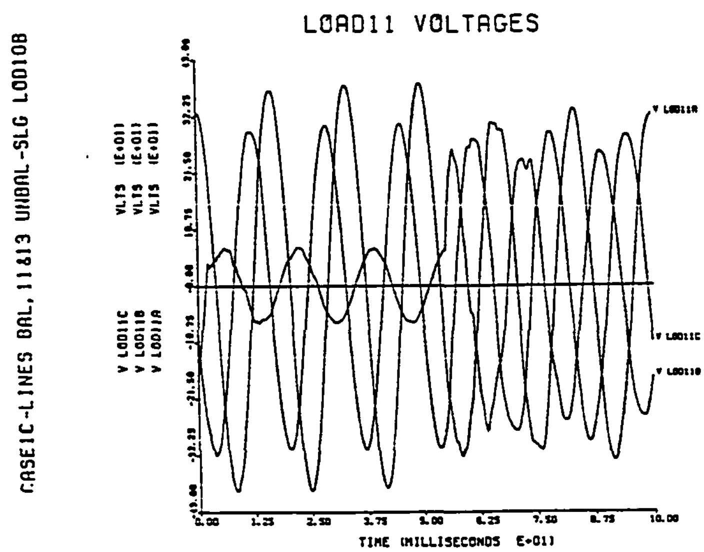

FIGURE 43. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1c)

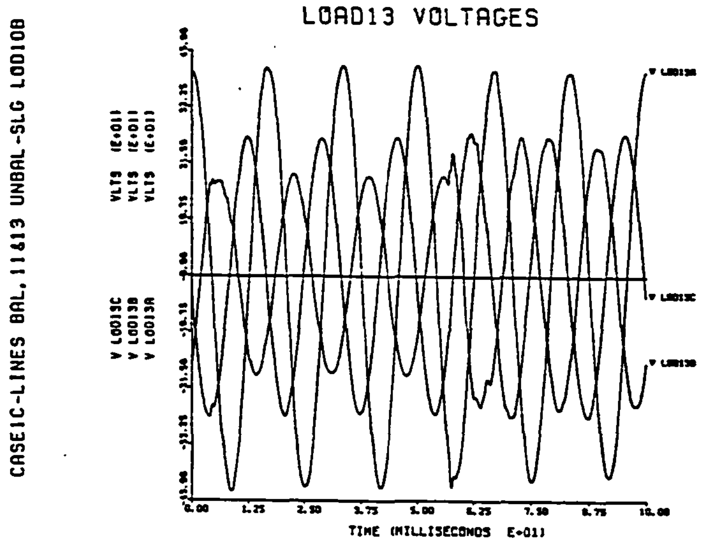

FIGURE 44. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 1c)

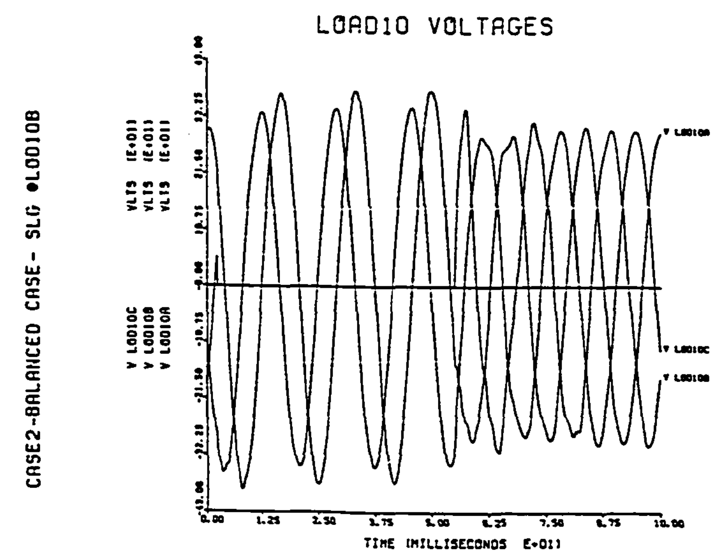

FIGURE 45. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 2)

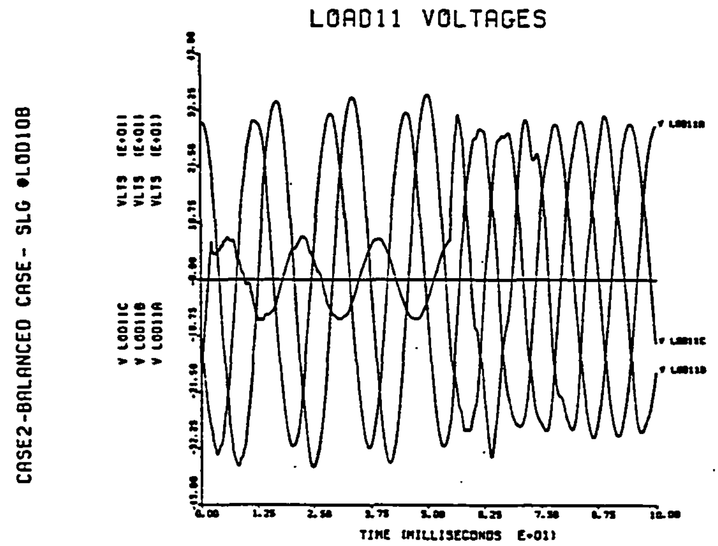

FIGURE 46. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 2)

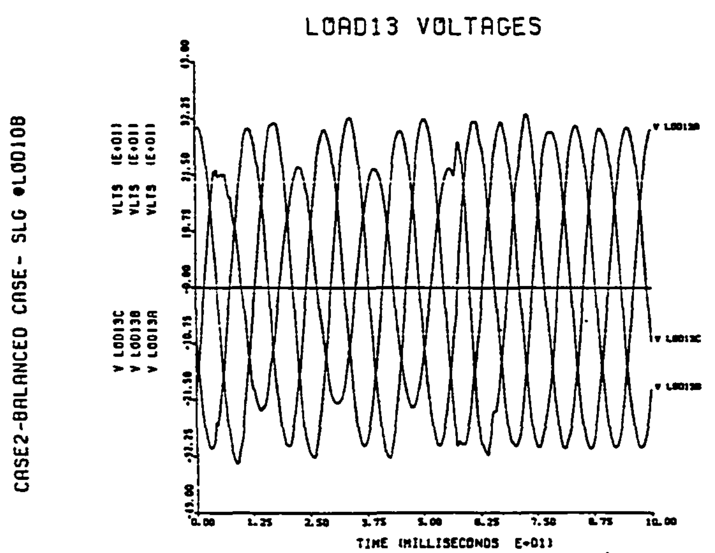

FIGURE 47. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 2)

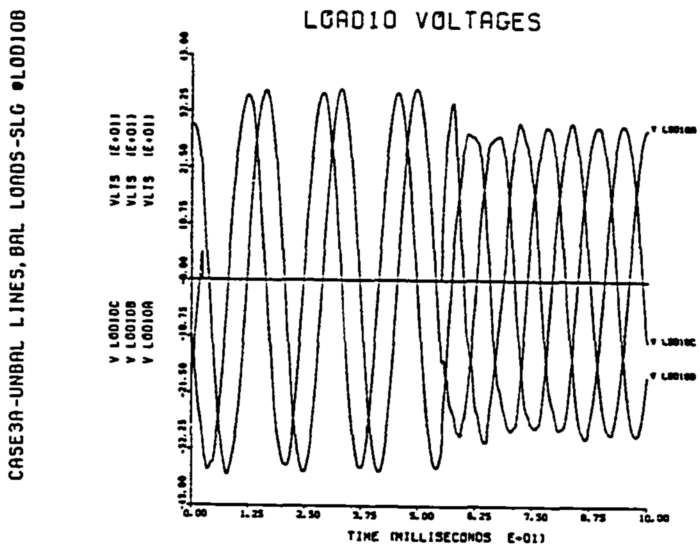

FIGURE 48. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3a)

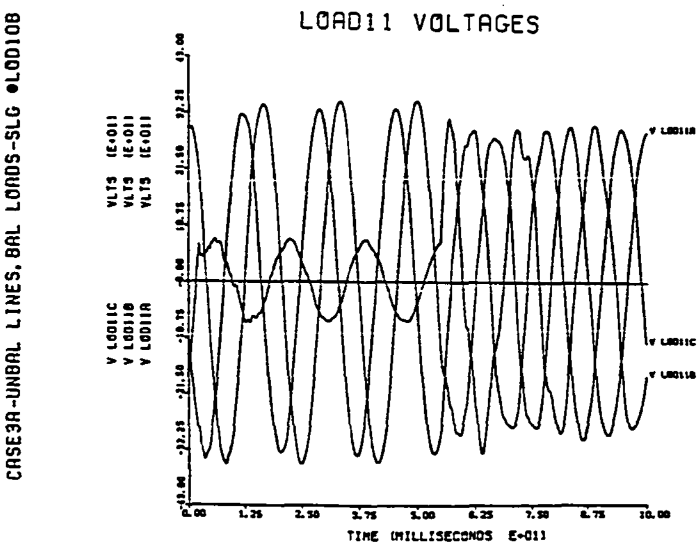

FIGURE 49. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3a)

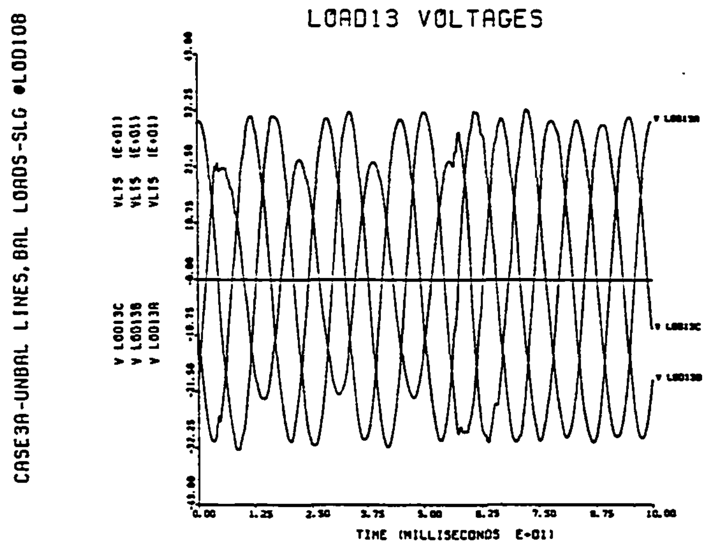

FIGURE 50. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3a)

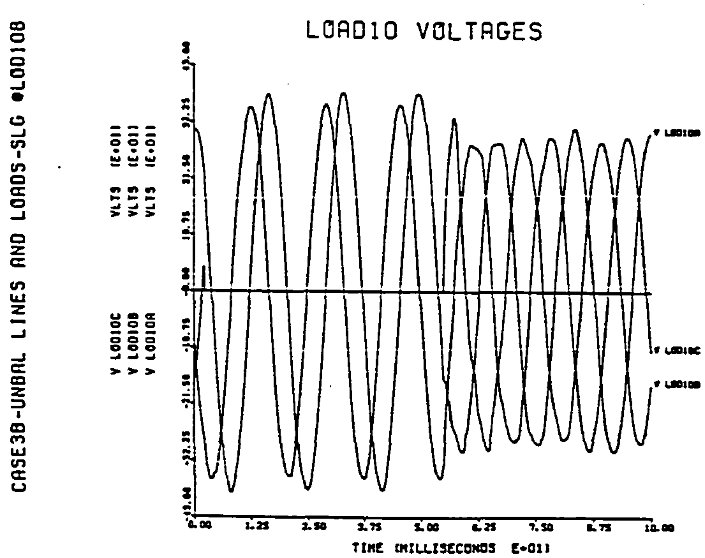

FIGURE 51. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3b)

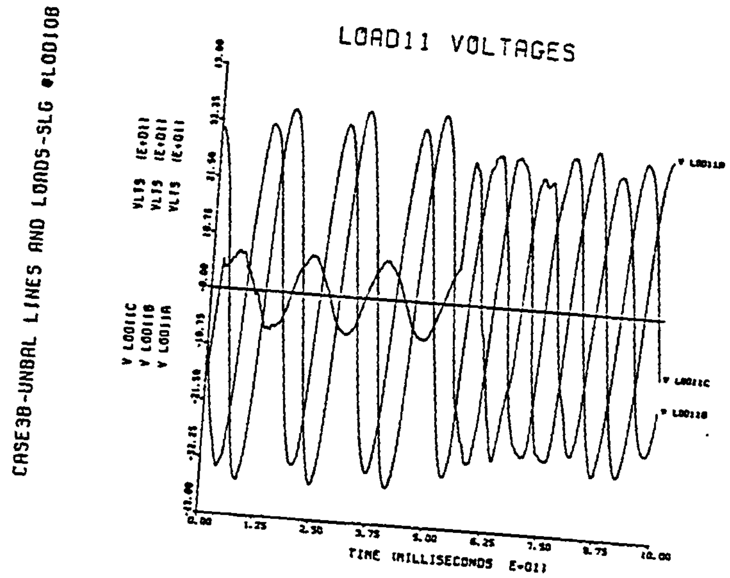

FIGURE 52. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3b)

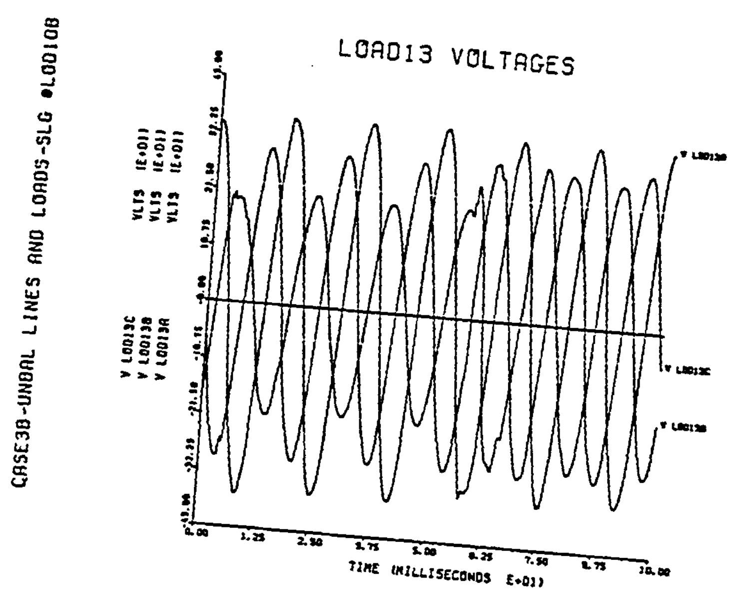

FIGURE 53. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3b)

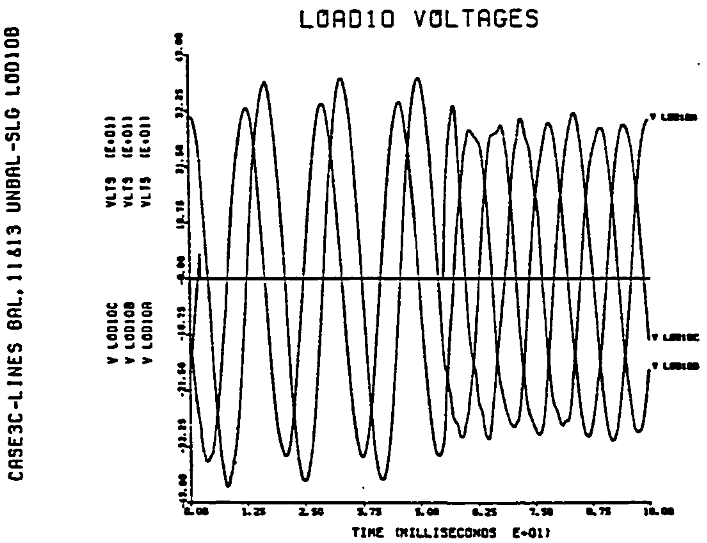

FIGURE 54. Transient response of bus LOAD10 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3c)

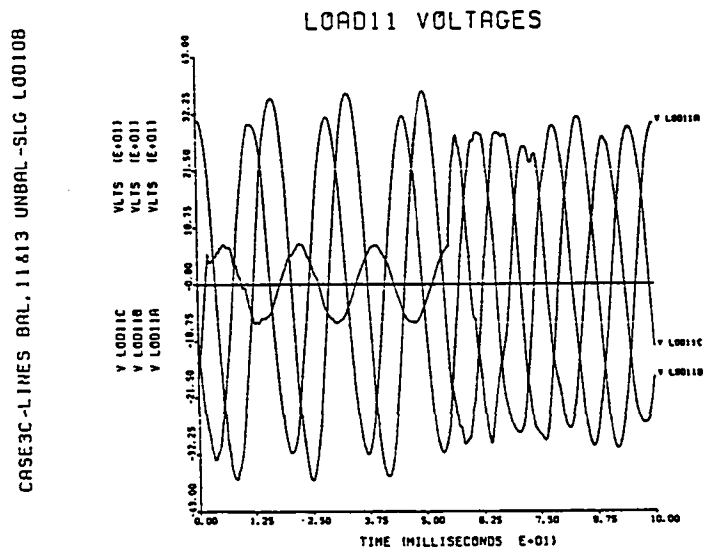

FIGURE 55. Transient response of bus LOAD11 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3c)

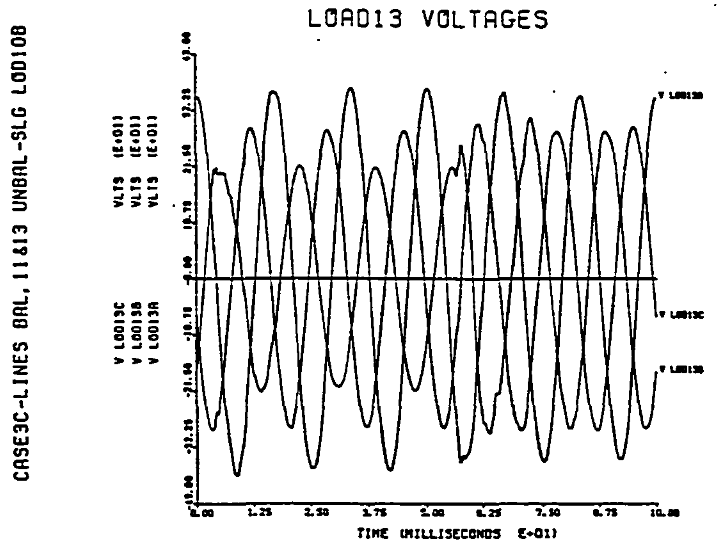

FIGURE 56. Transient response of bus LOAD13 phase voltages due to clearing a SLG fault on phase b near bus LOAD10 (case 3c)

VI. CONCLUSIONS

A comprehensive and rigorous analysis has been presented in this dissertation of EHV transmission system unbalances caused by untransposed transmission lines and unbalanced loads and their effects in power system analysis.

In the steady-state analysis, it is concluded that, in general, there is no simple way of obtaining the degree and the distribution of unbalances in the system. The only possible approach to this problem would be the three-phase analysis of the system since the overall effect of the transmission network, and load and their unbalances are all included in the study. However, it does not seem to be necessary to repeat this analysis every time the system loading changes. In a network with the fixed transmisison line configurations and lengths, the following steps may be taken to investigate the necessity of future three-phase analysis on the system under study (see Figure 57).

1. Unbalance analysis (three-phase representation) should be performed at least once when the transmission system is simulated with the maximum possible loading condition including all unbalanced loads that are present in the system. This would represent the maximum possible system imbalance.

   This step may be performed by using the newly developed method (system reduction method) to simplify the analysis.

2. At this step, the criteria imposed on the system (Chapter II, sections 1 and 3) need to be checked.

3. If the criteria are not met, then three-phase representation may be required in the future to ensure a safe and normal operation of the system.
4. If the criteria are met, then balanced three-phase representation will give a fairly good approximation.
5. It seems advisable to check the significance of unbalances whenever a new unbalanced load is expected. This may be checked by the unbalanced load criteria (see Eqs. 2.13, 2.14, 2.20, and 2.21).
6. If the unbalanced load criteria are not satisfied, then three-phase representation may be required. Otherwise, balanced three-phase representation would be satisfactory.
7. Unbalance analysis may be justifiable in a system with combination of unbalanced loads since unbalances due to each individual load may add and exceed the criteria limit.

In the electromagnetic transient analysis, the following has been concluded.

1. Untransposed transmission lines may be represented transposed.
2. Unbalanced loads should be represented as unbalanced.
3. Steady-state solution of the balanced three-phase system may be used as initial conditions to represent the generators, balanced loads, as well as unbalanced loads in network transient studies.

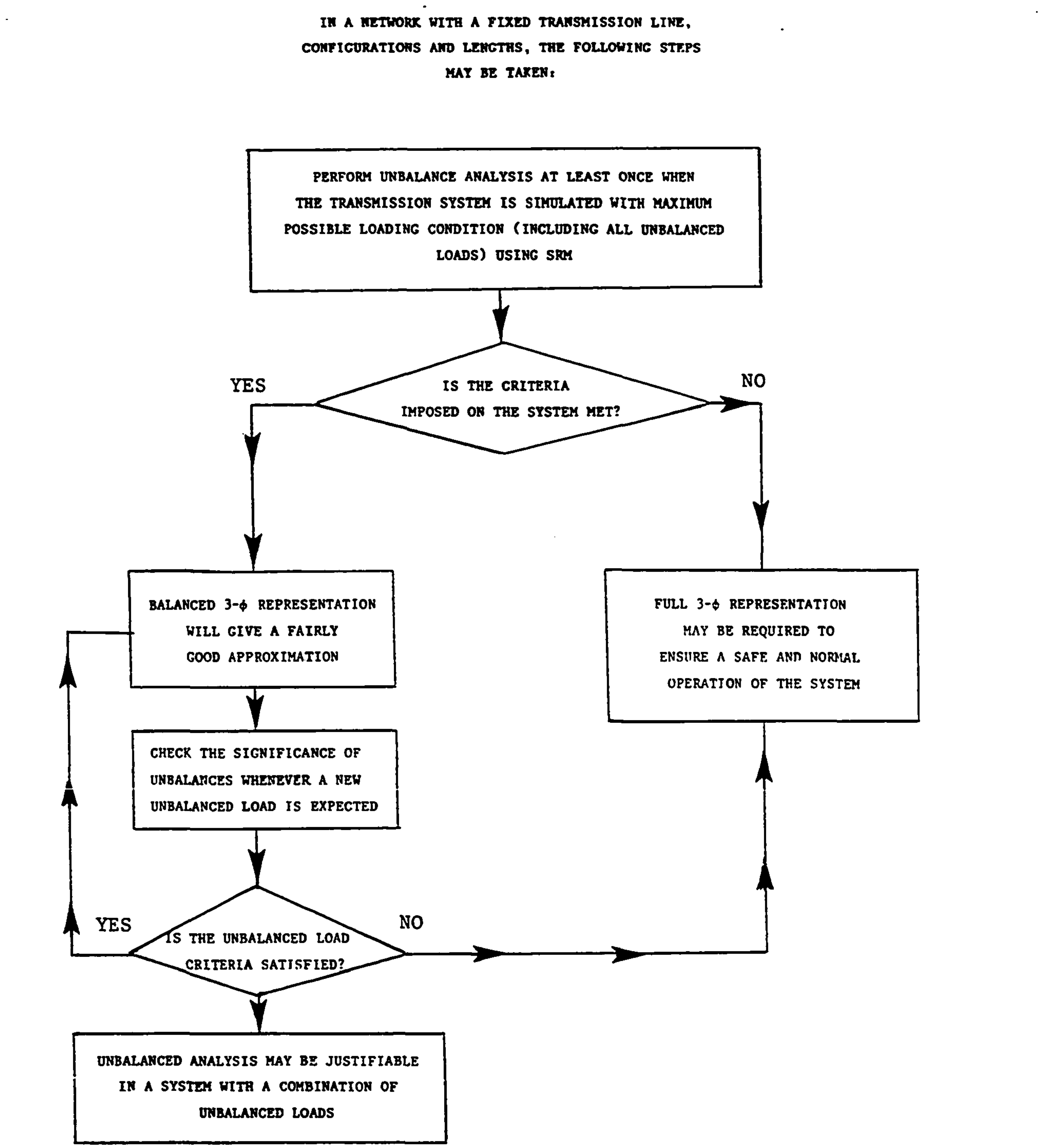

FIGURE 57. Decision making process to perform unbalance analysis

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IX. APPENDIX I. COMPUTER PROGRAMS USED IN THE ANALYSES

In this appendix, a brief description of the two major computer programs that were used in the analyses is presented.

A. Three-Phase Loadflow Program

1. Program description

The three-phase loadflow program [4,31] calculates the loading of the network for the general case, e.g., various combinations of the network and bus loading. These combinations are as follows:

1. Balanced network, balanced bus loading.
2. Balanced network, unbalanced bus loading.
3. Unbalanced network, balanced bus loading.
4. Unbalanced network, unbalanced bus loading.

The program will accommodate a network of up to 50 buses and 200 elements (lines, shunts, transformers, and line chargings). Mutual coupling between lines is taken into account, but off-nominal tap ratios and tap changing under load for transformers are not provided for within the program.

Gauss-Seidel's iterative scheme using the symmetrical component bus impedance model Z_{BUS} forms the basis of solution within the program. Data for the program are supplied by its data file and by the three-phase bus impedance program [32].

2. System representations

Transmission line impedances and line chargings are computed by using the transmission line parameters program [29].

Each generator, along with its step-up power transformer, basically is represented by balanced voltages behind the machine's synchronous reactance and transformer reactance [4,31].

Loads are represented phase by phase as constant MVA.

B. Electromagnetic Transient Program (EMTP)

1. Program description

EMTP is a steady state and transient state program that has been developed by Bonneville Power Administration [33]. This program can be used for one-phase and three-phase networks. The EMTP is capable of determining the steady-state phasor values of linear and nonlinear systems with a.c. sources at one frequency that can be used as initial conditions for electromagnetic transients. This program can also be used to obtain the frequency response of the network. For instance, the response of bus voltages, line voltage drops, line currents and power due to changes in frequency of the sources can be obtained.

In particular, the EMTP can be adopted to study and analyze the electromagnetic transients due to certain disturbances such as lightning discharges, faults, and switching surges in the system. The program appears to allow for an arbitrary interconnection of the following power network elements [33]:

- lumped representation of the network parameters
- multiphase multicircuit equivalency
- transposed and untransposed distributed parameter transmission lines (wave propagation is represented either as distortionless or lossy through lumped resistance approximations)
- nonlinear network elements, such as nonlinear resistances and inductances
- time-varying network elements
- switches with various switching criteria to simulate circuit
- breakers, spark gaps, diodes and other network connection changes
- voltage and current sources

Frequently used functions, such as sinusoids, surges, steps and ramps, are built into the program. Any or a combination of these functions may be used in simulations, as voltage or current sources.

2. Transmission line representation

Distributed parameter transmission line models were used to represent all transmission lines in the transient analysis.

a. Completely transposed transmission lines Multiphase lines, in general, with distributed parameters are said to be "electromagnetically balanced" if the self-impedances of all phases are equal among themselves, and if all mutual impedances between phases are equal. Such lines are similarly called "electrostatically balanced" if the capacitance to ground of all phases are equal to each other, and if all capacitances between phases are equal. The series impedance and shunt capacitance matrices of a completely balanced lines have the form

$$Z_{phase} = \begin{bmatrix} Z_s & Z_m & \cdots & Z_m \\ Z_m & Z_s & \cdots & Z_m \\ \vdots & \vdots & \ddots & \\ Z_m & Z_m & \cdots & Z_s \end{bmatrix}$$

$$C_{phase} = \begin{bmatrix} C_s & C_m & \cdots & C_m \\ C_m & C_s & \cdots & C_m \\ \vdots & \vdots & \ddots & \\ C_m & C_m & \cdots & C_s \end{bmatrix}$$

The balanced configuration allows for model decoupling by means of Karrenbauer's transformation [34,35]. The N-mutually-coupled equations in phase variables are converted into N-equivalent uncoupled one-phase equations which describe one ground return mode and N-1 line modes. The impedances of all N-1 line modes are identical. The diagonal matrices Z_{mode} and C_{mode} in the modal domain can then be obtained from

$$Z_{mode} = T_V^{-1} Z_{phase} T_i \tag{10.1}$$

$$C_{mode} = T_i^{-1} C_{phase} T_V \tag{10.2}$$

where

$$T_V = T_i = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1-N & \cdots & 1 \\ \vdots & \vdots & \ddots & \\ 1 & 1 & & 1-N \end{bmatrix}$$

$$T_V^{-1} = T_i^{-1} = \frac{1}{N} \begin{bmatrix} 1 & 1 & \cdot & \cdot & \cdot & 1 \\ 1 & -1 & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & & \cdot & \cdot \\ 1 & 0 & & & & -1 \end{bmatrix}$$

N = number of phases

The diagonalized matrices Z_{mode} and C_{mode} obtained from Eqs. 10.1 and 10.2 have the form

$$Z_{mode} = \begin{bmatrix} Z_g & & & \\ & Z_\ell & & \\ & & \ddots & \\ & & & Z_\ell \end{bmatrix}$$

$$C_{mode} = \begin{bmatrix} C_g & & & \\ & C_\ell & & \\ & & \ddots & \\ & & & C_\ell \end{bmatrix}$$

Subscripts g and ℓ stand for the ground return mode and line mode, respectively. The relationships between phase and mode quantities are then given by

$$Z_g = Z_s + (N-1)Z_m$$

and

$$Z_1 = Z_s - Z_m$$

Similar relationships hold for capacitances.

For a three-phase a.c. line, the ground return mode parameters are identical with the zero sequence parameters, and the line mode parameters are identical with the positive sequence parameters.

Using balanced matrices for double-circuit lines implies that: 1) the two circuits are identical in conductor type and tower configuration; 2) that each circuit is transposed within itself; 3) that coupling between the circuits exists only in the zero sequence. With these assumptions, the double circuit line would be described by a series impedance matrix of the form

$$Z_{phase} = \left[\begin{array}{ccc|ccc} Z_s & Z_m & Z_m & Z_p & Z_p & Z_p \\ Z_m & Z_s & Z_m & Z_p & Z_p & Z_p \\ Z_m & Z_m & Z_s & Z_p & Z_p & Z_p \\ \hline Z_p & Z_p & Z_p & Z_s & Z_m & Z_m \\ Z_p & Z_p & Z_p & Z_m & Z_s & Z_m \\ Z_p & Z_p & Z_p & Z_m & Z_m & Z_s \end{array}\right] \qquad (10.3)$$

and a similar structure for C_{phase}. The transposition scheme of Figure 58 would produce the matrix form (Eq. 10.3), provided both circuits have identical conductors and the tower configuration is symmetrical.

It can be shown [35] that matrices of the kind in Eq. 10.3 can be decoupled by the transformation matrices

$$T_V = T_i = \frac{1}{6}\left[\begin{array}{ccc|ccc} 1 & 2 & 2 & 1 & 0 & 0 \\ 1 & -4 & 2 & 1 & 0 & 0 \\ 1 & 2 & -4 & 1 & 0 & 0 \\ \hline 1 & 0 & 0 & -1 & 2 & 2 \\ 1 & 0 & 0 & -1 & -4 & 2 \\ 1 & 0 & 0 & -1 & 2 & -4 \end{array}\right]$$

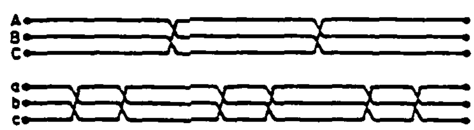

FIGURE 58· Transposition scheme for double-circuit line, producing coupling in zero sequence only

$$T_V^{-1} = T_i^{-1} = \left[\begin{array}{ccc|ccc} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ \hline 1 & 1 & 1 & -1 & -1 & -1 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \end{array}\right]$$

b. Untransposed transmission lines For an untransposed transmission line, the self-impedances (capacitances) of all phases as well as their mutual impedances (capacitances) are no longer equal among themselves. However, the line constants' matrices are still symmetric. Modal decoupling is still possible, but the transformation matrices required for the diagonalization process are now a characteristic of the line configuration, and must be supplied by the user. The diagonal matrices Z_{mode} and C_{mode} in the modal domain are obtained from Eqs. 10.1 and 10.2, where

$$T_i^{-1} = T_V^t \tag{10.4}$$

with the columns of T_V being the eigenvectors of the matrix product $(Z_{phase})(j\omega C_{phase})$ [33,35]. Voltages and currents in phase quantities are obtained from modal quantities with T_V and T_i as follows:

$$I_{phase} = T_i I_{mode}$$

and

$$V_{phase} = T_V \, V_{mode}$$

The modal transformation matrix T_i for the currents as well as the modal parameters R_{mode}, L_{mode}, and C_{mode} are not computed by the program and, therefore, must be supplied by the user.

Equation A.4 seems to be valid only if all eigenvalues of the matrix product $(Z_{phase})(j\omega C_{phase})$ are distinct. Since a balanced N-phase line has N-1 multiple eigenvalues, Eq. 10.4 will not be used. It is not valid, for instance, for symmetrical components applied to a balanced three-phase line, where

$$T_V = T_i = A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

and

$$T_V^{-1} = T_i^{-1} = A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

In general, modal surge impedances can be obtained by the square root of the ratio of the modal elements obtained from Eqs. 10.1 and 10.2, that is,

$$Z_{surge}^{mode} = \begin{bmatrix} \sqrt{\frac{L_1}{C_1}} & & \\ & \sqrt{\frac{L_2}{C_2}} & \\ & & \sqrt{\frac{L_3}{C_3}} \end{bmatrix}$$

where

L_1, L_2, L_3 = modal inductances

C_1, C_2, C_3 = modal capacitances from

$$Z_{\text{mode}i} = R_i + j\omega L_i$$

$$C_{\text{mode}i} = C_i \qquad i = 1,2,3$$

The phase surge impedance matrix then can be obtained by inverse transformation

$$Z_{\text{phase}}^{\text{phase}} = T_V \, Z_{\text{surge}}^{\text{mode}} \, T_i^{-1}$$

3. Generator equivalents

The internal induced voltages of generators are assumed to be balanced, while generators' terminal voltages depend on internal machine impedances and the imbalance in the machine currents. Generators are, therefore, represented by voltages behind the machine transient reactances (see Figure 59).

4. Load representation

Loads are represented as constant impedances to ground (see Figure 60).

5. Transformer representation

The model included in the EMTP takes into account the exciting currents. This model treats any N-winding one-phase transformer as N-coupled branches with branch impedance matrix Z = R+jωL. N-winding three-phase transformers are represented by three one-phase N-winding transformers [33]. In cases where transformers lie on the source side of the faulted or switched line (all winding connections may not be necessarily the same), such as in Figure 61a, the system behind the line could be represented as a simplified Thevenin equivalent [33]. This is shown in Figure 61b.

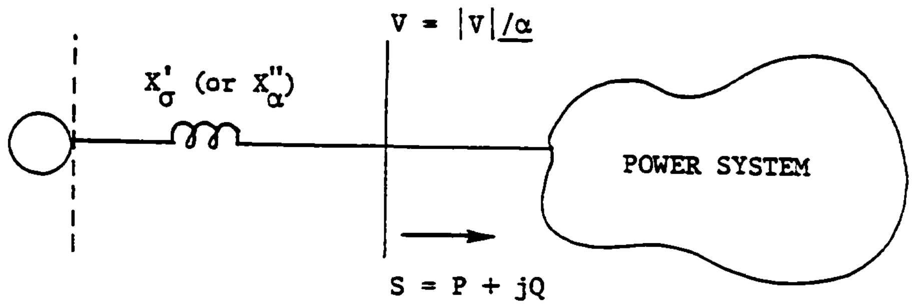

FIGURE 59. Generator equivalent

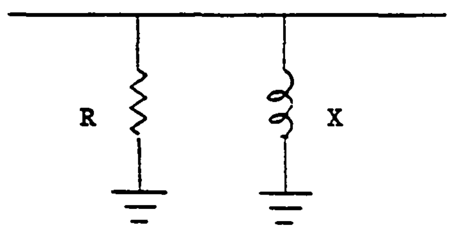

FIGURE 60. Load equivalent

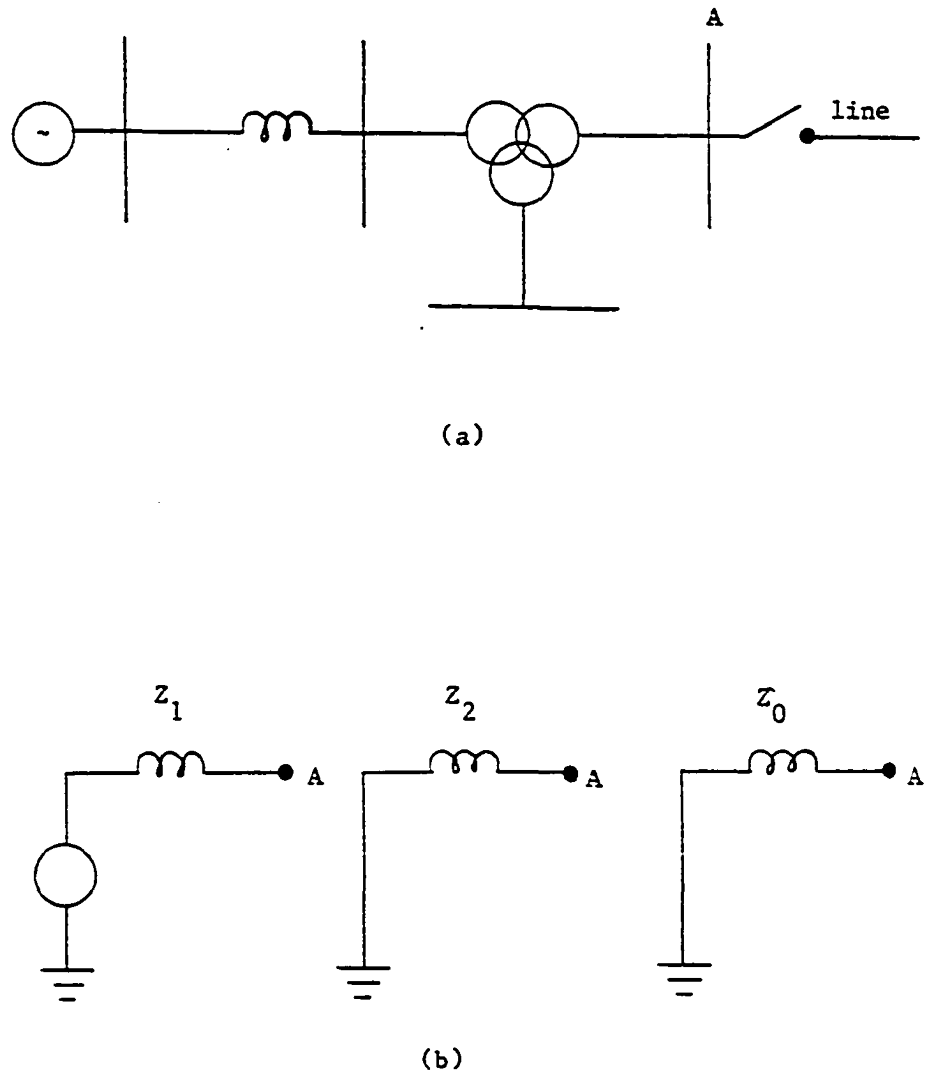

FIGURE 61. Source equivalent:

(a) transformers on the source side

(b) positive, negative, and zero sequence equivalent circuits of Figure 61a

Caution should be used with the transformer model in the EMTP. The accuracy of this model for a small exciting current is questionable because the Z matrix is obtained from inversion of an almost singular Y matrix. If the exciting currents are ignored, which is often the case, the model available in EMTP cannot be used.

Reference 36 describes a transformer model that ignores the exciting current and gives the equivalent admittance matrix. But, since the matrix is singular, it cannot be inverted and, therefore, that model cannot be incorporated into the EMTP either. Therefore, unless a better transformer representation is modeled, two-winding transformers will be modeled by their series impedances [3,28] per phase and three-winding transformers will be modeled as an equivalent star [28].

In short, to represent the generators and loads in EMTP, the following procedures are performed:

1. Obtain the powers and voltages at the generation and load buses from the three-phase loadflow analysis.
2. Knowing V, P, and Q at the generation buses and the machines' reactances, generators are represented by fictitious buses, one bus behind the generation buses (see Figure 59).
3. Knowing V, P, and Q at load buses, loads are represented as constant impedances to ground (see Figure 60).

$$R = \frac{|V|^2}{P} \text{ and } X = \frac{|V|^2}{Q}$$

A computer program has been developed that reads in Z_{phase}, C_{phase} of transmission lines, generator terminal voltages, and loads P and Q per phase and writes out R_{mode}, L_{mode}, C_{mode} of transmission lines along with the transformation matrix T_i, equivalent sources, and load equivalent R and X. The format of this output matches the format of the EMTP input and, therefore, can be used directly as the input to EMTP. A listing of this program in presented in this appendix.

6. FORTRAN program to compute the transmission line modal quantities, generator and load equivalents

```
C     MAIN
C
C     ***********************************************************
C     *   FORTRAN PROGRAM TO COMPUTE THE MODAL PARAMETERS      *
C     *   OF UNTRANSPOSED TRANSMISSION LINES. IT ALSO          *
C     *   DETERMINES THE GENERATORS AND LOADS EQUIVALENTS.     *
C     ***********************************************************
C
C
C
C     THIS PROGRAM USES ZPHASE, CPHASE OF UNTRANSPOSED LINES,
C     (P+JQ)/PHASE AND VOLTAGES AT THE GENERATORS TERMINALS AND
C     LOADS TO COMPUTE RMODE, LMODE, CMODE ALONG WITH THE
C     CURRENT TRANSFORMATION MATRIX TI, GENERATORS EQUIVALENTS,
C     AND LOAD EQUIVALENT R'S AND X'S.
C     THE OUTPUT OF THIS PROGRAM CAN BE USED DIRECTLY AS A PART OF
C     THE INPUT TO EMTP.
C
C
C
      REAL WK(6)
      COMPLEX TV(6,6),TVI(6,6),TVT(6,6),TI(6,6),WA(48),OUT(6,6)
      COMPLEX Z(6,6),Y(6,6),ZS(3,3)
      CHARACTER*6 NAME
      CHARACTER*70 CASE
C
C
C
C     PHASE TO MODAL TRANSFORMATION "MOD"
C     M=NO. OF PHASES
C     FOR A BALANCED CASE, PUT CASE='BALANCE'
C     FOR AN UNBALANCED CASE, PUT CASE='UNBALANCE'
      READ(12,*)CASE
      WRITE(6,14)CASE
   10 READ(12,*)M
      IF(M.EQ.999)GO TO 110
      READ(12,*)NAME
      WRITE(6,13)NAME
      CALL EIGENV(M,Z,Y,TV)
      CALL UNITY(M,TVI)
      CALL LEQ2C(TV,M,6,TVI,M,6,0,WA,WK,IER)
      DO 100 I=1,M
      DO 100 J=1,M
  100 TVT(I,J)=TV(J,I)
      CALL UNITY(M,TI)
      CALL LEQ2C(TVT,M,6,TI,M,6,0,WA,WK,IER)
```

```
      WRITE(6,400)
      CALL WRITEO(M,TI)
      CALL MULT(6,6,6,M,M,M,TVI,Z,OUT)
      CALL MULT(6,6,6,M,M,M,OUT,TI,Z)
      WRITE(6,401)
      CALL WRITEO(M,Z)
      CALL MULT(6,6,6,M,M,M,TVT,Y,OUT)
      CALL MULT(6,6,6,M,M,M,OUT,TV,Y)
      WRITE(6,402)
      CALL WRITEO(M,Y)
C
C
C     EMTP FORMAT
C
C
C
C     CONVERT MHOS/MI TO MICRO-MHOS/MI
      DO 399 I=1,M
 399  Y(I,I)=Y(I,I)*1000000.
      WRITE(6,452)NAME,NAME,REAL(Z(1,1)),AIMAG(Z(1,1)),AIMAG(Y(1,1))
      WRITE(6,453)NAME,NAME,REAL(Z(2,2)),AIMAG(Z(2,2)),AIMAG(Y(2,2))
      WRITE(6,454)NAME,NAME,REAL(Z(3,3)),AIMAG(Z(3,3)),AIMAG(Y(3,3))
      IF(M.EQ.3)GO TO 1000
      WRITE(6,456)NAME,NAME,REAL(Z(4,4)),AIMAG(Z(4,4)),AIMAG(Y(4,4))
      WRITE(6,457)NAME,NAME,REAL(Z(5,5)),AIMAG(Z(5,5)),AIMAG(Y(5,5))
      WRITE(6,458)NAME,NAME,REAL(Z(6,6)),AIMAG(Z(6,6)),AIMAG(Y(6,6))
 1000 CONTINUE
      DO 451 I=1,M
 451  WRITE(6,455)(REAL(TI(I,J)),J=1,M)
 400  FORMAT(20X,'*** TI MATRIX ***')
 401  FORMAT(20X,'*** ZMODE OHMS/MI ***')
 402  FORMAT(20X,'*** YMODE MHOS/MI ***')
 452  FORMAT(1X,'-1',A4,'A ',A4,'A ',12X,F6.4,F6.4,F6.2,
     1' ***.*',1X,'0')
 453  FORMAT(1X,'-2',A4,'B ',A4,'B ',12X,F6.4,F6.4,F6.2,
     1' ***.*',1X,'0')
 454  FORMAT(1X,'-3',A4,'C ',A4,'C ',12X,F6.4,F6.4,F6.2,
     1' ***.*',1X,'0')
 456  FORMAT(1X,'-4',A4,'A ',A4,'A ',12X,F6.4,F6.4,F6.2,
     1' ***.*',1X,'0')
 457  FORMAT(1X,'-5',A4,'B ',A4,'B ',12X,F6.4,F6.4,F6.2,
     1' ***.*',1X,'0')
 458  FORMAT(1X,'-6',A4,'C ',A4,'C ',12X,F6.4,F6.4,F6.2,
     1' ***.*',1X,'0')
 455  FORMAT(1X,6F12.5)
      GO TO 10
 110  CONTINUE
C
C
C
```

```
C     INPUT: LOADS CONSTANT P,Q- OUTPUT: LOADS CONSTANT Z TO GROUND
C
      READ(12,*)CASE
      IF(CASE.EQ.'BALANCE')GO TO 105
      CALL SYSU
      GO TO 200
  105 CALL SYSB
  200 CONTINUE
C
C
C
C     FIND THE EQUIVALENT SOURCE VOLTAGES
C
      READ(12,*)NSRCE
      DO 300 I=1,3
      DO 300 J=1,3
  300 ZS(I,J)=(0.,0.)
      ZS(1,1)=(0.,.02)
      ZS(2,2)=(0.,.02)
      ZS(3,3)=(0.,.02)
      DO 301 I=1,NSRCE
  301 CALL SRCE(CASE,ZS)
   13 FORMAT(50X,'***',A5,' ***')
   14 FORMAT(50X,'***',A40,'***')
      STOP
      END
C
C
C
      SUBROUTINE EIGENV(M,Z,Y,TV)
      COMPLEX A(6,6),EIGA(6),EIGB(6),TV(6,6),Z(6,6),Y(6,6),WK(6,12)
      COMPLEX B(6,6)
      WRITE(6,10)
      DO 100 I=1,M
  100 READ(12,*)(Z(I,J),J=1,I)
      DO 101 I=1,M
      DO 101 J=1,I
  101 Z(J,I)=Z(I,J)
      CALL WRITEO(M,Z)
      WRITE(6,12)
      DO 120 I=1,M
  120 READ(12,*)(Y(I,J),J=1,I)
      DO 102 I=1,M
      DO 102 J=1,I
  102 Y(J,I)=Y(I,J)
      CALL WRITEO(M,Y)
      CALL MULT(6,6,6,M,M,M,Z,Y,A)
      IA=6
      IB=6
      IZ=6
```

```
      IJOB=2
      CALL UNITY(M,B)
      CALL EIGZC(A,IB,B,IB,M,IJOB,EIGA,EIGB,TV,IZ,WK,INFER,IER)
      IF(IER.NE.0.OR.INFER.NE.0)PRINT,'IER=',IER,'INFER=',INFER
 10   FORMAT(20X,'*** Z MATRIX OHMS/MI ***')
 12   FORMAT(20X,'*** Y MATRIX MHOS/MI ***')
      RETURN
      END
C
C
C
      SUBROUTINE WRITEO(M,INPUT)
      COMPLEX INPUT(6,6)
      DO 100 I=1,M
      WRITE(6,400)(REAL(INPUT(I,J)),J=1,M)
      WRITE(6,400)(AIMAG(INPUT(I,J)),J=1,M)
 100  WRITE(6,401)
 400  FORMAT(10X,6(E15.6,2X))
 401  FORMAT('-')
      RETURN
      END
C
C
C
      SUBROUTINE UNITY(N,B)
      COMPLEX B(6,6)
      DO 100 I=1,N
      DO 100 J=1,N
      IF(I.EQ.J)B(I,J)=(1.,0.)
      IF(I.NE.J)B(I,J)=(0.,0.)
 100  CONTINUE
      RETURN
      END
C
C
C
      SUBROUTINE MULT(ID1,ID2,ID3,K1,K2,K3,MAT1,MAT2,OUT)
      COMPLEX MAT1(ID1,ID2),MAT2(ID2,ID3),OUT(ID1,ID3),SUM
      INTEGER L
      DO 95 I=1,K1
      DO 95 L=1,K3
      SUM=(0.,0.)
      DO 94 J=1,K2
 94   SUM=SUM+MAT1(I,J)*MAT2(J,L)
      OUT(I,L)=SUM
 95   CONTINUE
      RETURN
      END
C
C
```

```
C
C
      SUBROUTINE SYSB
      REAL RE,IM
      CHARACTER*5 NAME
      COMPLEX S
      READ(12,*)NLOAD
C
      DO 200 I=1,NLOAD
      READ(12,*)NAME,S,V
      PP=REAL(S)
      QQ=AIMAG(S)
      FAC=100.*V*V*1190.25/(PP*PP+QQ*QQ)
      RE=PP*FAC
      IM=QQ*FAC
      WRITE(6,1)NAME,RE,IM
      WRITE(6,2)NAME,RE,IM
  200 WRITE(6,3)NAME,RE,IM
  1   FORMAT(3X,A5,'A',18X,2F6.1)
  2   FORMAT(3X,A5,'B',18X,2F6.1)
  3   FORMAT(3X,A5,'C',18X,2F6.1)
      RETURN
      END
C
C
C
      SUBROUTINE SYSU
      COMPLEX S
      REAL V,R,X,P,Q
      CHARACTER*6 NAME
C
      READ(12,*)NLOAD
      DO 100 I=1,NLOAD
      DO 100 J=1,3
      READ(12,*)NAME,S,V
      P=REAL(S)
      Q=AIMAG(S)
      FAC=(100./3.)*V*V*1190.25/(P*P+Q*Q)
      R=FAC*P
      X=FAC*Q
      IF(J.EQ.1)GO TO 20
      IF(J.EQ.2)GO TO 30
      WRITE(6,3)NAME,R,X
      GO TO 100
   20 WRITE(6,1)NAME,R,X
      GO TO 100
   30 WRITE(6,2)NAME,R,X
  100 CONTINUE
  1   FORMAT(3X,A5,'A',18X,2F6.1)
  2   FORMAT(3X,A5,'B',18X,2F6.1)
```

```
3      FORMAT(3X,A5,'C',18X,2F6.1)
       RETURN
       END
       SUBROUTINE SRCE(CASE,ZS)
       REAL MAGI(3),MAGV(3),ANGI(3),ANGV(3)
       COMPLEX VLV(3),VHV(3),CI(3),ZS(3,3)
       CHARACTER*70 CASE
       CHARACTER*6 NAME
       VBASE=281.691
       FREQ=60.
       READ(12,*)NAME
       IF(CASE.EQ.'BALANCE')GO TO 100
       READ(12,*)(MAGI(I),ANGI(I),I=1,3)
       READ(12,*)(MAGV(I),ANGV(I),I=1,3)
       GO TO 200
 100   READ(12,*)MAGI(1),ANGI(1)
       READ(12,*)MAGV(1),ANGV(1)
       DO 150 I=2,3
       MAGI(I)=MAGI(1)
       MAGV(I)=MAGV(1)
       IF(I.EQ.2)ANGI(I)=ANGI(1)-120.
       IF(I.EQ.3)ANGI(I)=ANGI(1)+120.
       IF(I.EQ.2)ANGV(I)=ANGV(1)-120.
 150   IF(I.EQ.3)ANGV(I)=ANGV(1)+120.
 200   CALL RECT(MAGI,ANGI,CI)
       CALL RECT(MAGV,ANGV,VHV)
       CALL MULT(3,3,1,3,3,1,ZS,CI,VLV)
       DO 10 I=1,3
 10    VLV(I)=(VLV(I)+VHV(I))*VBASE
       CALL POLAR(3,VLV,MAGV,ANGV)
       WRITE(6,20)NAME,MAGV(1),FREQ,ANGV(1)
       WRITE(6,21)NAME,MAGV(2),FREQ,ANGV(2)
       WRITE(6,22)NAME,MAGV(3),FREQ,ANGV(3)
 20    FORMAT(1X,'14',A5,'A',2X,F10.3,F10.2,F10.3,25X,'-1.')
 21    FORMAT(1X,'14',A5,'B',2X,F10.3,F10.2,F10.3,25X,'-1.')
 22    FORMAT(1X,'14',A5,'C',2X,F10.3,F10.2,F10.3,25X,'-1.')
       RETURN
       END
C
C
C
       SUBROUTINE RECT(MAG,ANG,Z)
       REAL MAG(3),ANG(3),IM,R
       COMPLEX Z(3)
       PI=3.1415927
       DO 100 I=1,3
       ANG(I)=ANG(I)*PI/180.
       R=MAG(I)*COS(ANG(I))
       IM=MAG(I)*SIN(ANG(I))
 100   Z(I)=CMPLX(R,IM)
```

```
      RETURN
      END
C
C
C
      SUBROUTINE POLAR(M,INPUT,MAG,ANG)
      REAL MAG(M),ANG(M)
      COMPLEX INPUT(M)
      PI=3.1415926
      DO 200 I=1,M
      RI=REAL(INPUT(I))
      AI=AIMAG(INPUT(I))
      MAG(I)=SQRT(RI**2+AI**2)
      IF(RI.EQ.0.)GO TO 49
      ANG(I)=ATAN2(AI,RI)
      ANG(I)=ANG(I)*180./PI
      GO TO 200
 49   IF(AI.EQ.0.)ANG(I)=0.
      IF(AI.NE.0.)ANG(I)=90.
 200  CONTINUE
      RETURN
      END
C
```

X. APPENDIX II. SYSTEM REDUCTION METHOD

A. FORTRAN Program Listings

```
C     MAIN PROGRAM
C
C     ***************************************************
C     *     SYSTEM REDUCTION METHOD FORTRAN PROGRAM     *
C     ***************************************************
C
      INTEGER P,Q,R,S,EM,ES,NODES(300,2),ME(20,2),TYP3(50),MTP(20)
      INTEGER T1,M,N,TP(300),L,NODE3(65,2),ME3(10,2),MFLAG,ESN
      INTEGER SIGN,LVBUS,HVBUS,OUTTP,INFO
      COMPLEX ZS,ZM,YBUS(86,86),WA(8280)
      COMPLEX YM,NYSS(3,3),BC(195),DET,VL(3,1),MATT(3,3),MAT6(6,6)
      COMPLEX YBUS0(85,85),YNEW(85,85),Z1(85,85),Z2(85,1)
      COMPLEX Z3(1,85)
      COMPLEX ZNEW(85,85),ZT1,ZTM2,HVOLT(3),YT1,YTM2
      COMPLEX IGEN(3),IGENT(3),GVOLT(3),HVOLTT(3),SS(3)
      COMPLEX ZZ,TZ(300),YBUS1(85,85)
      COMPLEX ZSS(3,3),YSS(3,3),Y3F1(195,195),ZMUT(63,63)
      COMPLEX ZZ1(3,3),YMUT(63,63),YPQ(3,3),YM1(3,3),YM2(3,3),YRS(3,3)
      COMPLEX NYRS(3,3),NYPQ(3,3),NYM1(3,3),NYM2(3,3)
      COMPLEX ZZS1(3,3),ZZM1(3,3),ZZM2(3,3),ZZS2(3,3)
      COMPLEX STYP0(100),STYP1(100),STYP2(100),MTYP(10)
      COMPLEX YBUS2(85,85)
      COMPLEX Y3F2(240,240),VG(150,1),V(90,1),VV(3),VGG(50)
      COMPLEX Y1V(90,90),Y1VI(90,90),YOUT3(90,150)
      COMPLEX STYP3(50,3,3),MTYP3(10,6,6),Y2V(90,150)
      COMPLEX ZT(40,40),YT(40,40),YTYP3(50,3,3),DV(3)
      COMPLEX VVV(3,30),ILINE(3),ILENT(3),OUT1(3),OUT2(3)
      COMPLEX VVVT(3,30),VVT(3),POWER(3),YMTYP3(63,63)
      COMPLEX YBUS11(65,65),YBUS22(65,65),YBUS00(65,65)
      COMPLEX SA,SB,SC,YY(3,3),AI(3,3),A(3,3),OUTT(3,3)
      REAL WK(63),MAG(90),ANG(90),MAGI(3),MAGV(3),ANGI(3),ANGV(3)
      REAL ILEN,IILEN(240),IMLEN(10)
      REAL*8 TITLE(10),NAME(35)
      COMMON BMVA
C
C
C
C
C
C
C
C
C
C
```

```
C     PROGRAM GOALS:
C
C     PHASE 1:                COMPUTING THE EQUIVALENT YBUS FOR THE
C                             SYSTEM OUTSIDE THE STUDY AREA WHICH IS
C                             ASSUMED TO BE BALANCED.
C     IT COMPUTES 3 SEQUENCE YBUSES, REDUCES EACH BY FAST
C     KRON REDUCTION METHOD TAKING ADVANTAGE OF SYMMETRIC AND SPARSE
C     Y MATRICES, THEN COMBINES THEM TO MAKE 3-PHASE YBUS 0,1,2.
C    THE REDUCED MATRIX REPRESENTS THE EQUIVALENCE OF THE SYSTEM
C    OUTSIDE THE STUDY AREA.
C
C    PHASE 2:               COMPUTING THE STUDY AREA YBUS
C    THE EQUIVALENT YBUS WILL BE MODIFIED BY ADDING INSIDE OF THE
C    STUDY AREA ELEMENTS TO EDGES OF STUDY AREA INCLUDING ALL THE
C    LOADS WHICH AE REPRESENTED BY THE ADMITTANCE MATRICES.
C    THE NEW MODIFIED YBUS REPRESENTS THE FINAL FORM OF THE SYSTEM
C    YBUS.
C    PHASE 3:      ESTIMATE UNBALANCES IN THE REGION OF INTEREST
C
C    BY APPLYING THE POSITIVE SEQUENCE VOLTAGES AT THE INTERNAL NODES
C   OF THE GENERATORS, VOLTAGES, CURRENTS, AND POWER FLOWS INSIDE OF
C   STUDY AREA CAN BE COMPUTED.
C
C
C   PRINTOUT OPTIONS:
C   INFO=0             PRINT ONLY THE UNBALANCES AT THE GENERATORS HIGH
C                      VOLTAGE BUSES.
C   INFO=1             PRINT INFO=0 OPTION PLUS LINE FLOWS INFORMATION .
C
C
C
C
C
C      INTEGER P,Q,R,S,EM,ES,NODES(NE,2),ME(NOC,2),TYP3(INTP),MTP(NOC)
C      INTEGER T1,M,N,TP(NE),L,NODE3(NE3,2),ME3(NOC3,2),MFLAG,ESN
C      INTEGER SIGN,LVBUS,HVBUS,OUTTP
C      COMPLEX ZS,ZM,YBUS(NBB,NBB),WA(NWA)
C      COMPLEX YM,NYSS(3,3),BC(N13F),DET,VL(3,1),MATT(3,3),MAT6(6,6)
C      COMPLEX YBUSO(NB,NB),YNEW(NB,NB),Z1(NB,NB),Z2(NB,1),Z3(1,NB)
C      COMPLEX ZNEW(NB,NB),ZT1,ZTM2,HVOLT(3),YT1,YTM2
C      COMPLEX IGEN(3),IGENT(3),GVOLT(3),HVOLTT(3),SS(3)
C      COMPLEX ZZ,TZ(NE),YBUS1(NB,NB),Z(NT,NT)
C      COMPLEX ZSS(3,3),YSS(3,3),Y3F1(N13F,N13F),ZMUT(MAX.NMM*NMM)
C      COMPLEX ZZ1(3,3),YMUT(MAX.NMM*NMM),YPQ(3,3),YM1(3,3)
C      COMPLEX YM2(3,3),YRS(3,3)
C      COMPLEX NYRS(3,3),NYPQ(3,3),NYM1(3,3),NYM2(3,3)
C      COMPLEX ZZS1(3,3),ZZM1(3,3),ZZM2(3,3),ZZS2(3,3)
C      COMPLEX STYPO(OUTTP),STYP1(OUTTP),STYP2(OUTTP),MTYP(OUTMTP)
C      COMPLEX YBUS2(NB,NB)
C      COMPLEX Y3F2(NT3,NT3),VG(NGEN3,1),V(NB3,1),VV(3),VGG(IGN)
```

```
C       COMPLEX Y1V(NB3,NB3),Y1VI(NB3,NB3),YOUT3(NB3,NGEN3)
C       COMPLEX STYP3(INTP,3,3),MTYP3(OUTMTP,6,6),Y2V(NB3,NGEN3)
C       COMPLEX ZT(NM,NM),YT(NM,NM),YTYP3(INTP,3,3),DV(3)
C       COMPLEX VVV(3,NSB),ILINE(3),ILENT(3),OUT1(3),OUT2(3)
C       COMPLEX VVVT(3,NSB),VVT(3),POWER(3),YMTYP3(MAX.NMM*NMM)
C       COMPLEX YBUS11(N1,N1),YBUS22(N1,N1),YBUS00(N1,N1)
C       COMPLEX SA,SB,SC,YY(3,3),AI(3,3),A(3,3),OUTT(3,3)
C       REAL WK(NE),MAG(NB3),ANG(NB3),MAGI(3),MAGV(3),ANGI(3),ANGV(3)
C       REAL ILEN,IILEN(NE3),IMLEN(NOC3)
C       CHARACTER*80 TITLE
C       CHARACTER*8 NAME(NBG3)
C
C
C
C       DEFINITION OF INDICES : OUTSIDE OF STUDY AREA
C
C       NE-TOTAL NO. OF ELEMENTS OUTSIDE OF THE STUDY AREA (LINES
C          SERIES IMPEDANCES, SHUNTS, MUTUAL IMPEDANCES, TRANSFORMERS
C          LEAKAGE REACTANCES, ETC.)
C       NOC-NO. OF COUPLED ELEMENTS
C       OUTTP-TOTAL NO. OF ELEMENT TYPES ENTERED
C       N1-NO. OF NODES OF THE EDGE OF STUDY AREA PLUS NO. OF GENERATOR
C          NODES (ESN+IGN)
C       IGN-TOTAL NO. OF GENERATORS INSIDE & OUTSIDE OF STUDY AREA
C       NT-TOTAL NO. OF BUSES IN THE SYSTEM INCLUDING GEN. INTERNAL NODES
C       NWA-DIMENSION OF COMPLEX WORK AREA (MAX.NMM*(NMM+2))
C       NB-TOTAL NO. OF BUSES IN THE SYSTEM INCLUDING GEN. INTERNAL NODES
C          EXCLUDING THE NODES INSIDE OF THE STUDY AREA (NB=NT-ISN)
C       NM-NO. OF MUTUALLY COUPLED ELEMENTS=NOC*2
C       NBB=NB+1
C       OUTMTP-NO. OF MUTUAL ELEMENT TYPES OUTSIDE OF STUDY
C            STUDY AREA
C
C
C
C       DEFINITION OF TERMS USED : INSIDE OF STUDY AREA
C
C       NSB-NO. OF STUDY AREA BUSES (EDGE BUSES PLUS INSIDE NODES;I.E.
C           ESN+ISN)
C       ESN-NO. OF NODES ON THE EDGE OF STUDY AREA
C       ISN-NO. OF NODES INSIDE OF STUDY AREA
C       INTP-NO. OF ELEMENT TYPES ENTERED
C       NOC3-NO. OF COUPLINGS
C      N13F-3*(NO. OF NODES RETAINED EXCLUDING THE NODES INSIDE OF STUDY)
C       AREA)=3*(ESN+IGN)=3*N1
C       NT3-3*(TOTAL NO. OF NODES RETAINED)=N13F+3*ISN
C       IGN3-3*(TOTAL NO. OF GENERATOR INTERNAL NODES)=3*IGN
C       NB3-3*(NO. OF STUDY AREA BUSES )=3*NSB
C       NE3-TOTAL NO. OF ELEMENTS INSIDE OF THE STUDY AREA (LINES
C       SERIES IMPEDANCES, SHUNTS, MUTUAL IMPEDANCES, TRANSFORMERS
```

```
C     LEAKAGE REACTANCES, ETC.)
C     NMM=NM3*3-2+5
C     NM3-NO. OF MUTUALLY COUPLED ELEMENTS=NOC3*2
C     SIGN-NO. OF GENERATORS INSIDE OF STUDY AREA
C     NBG3-TOTAL NO. OF NODES AND GENERATORS INSIDE OF STUDY AREA
C         =ESN+ISN+SIGN
C
C
C
C
C
      READ(12,2999)(TITLE(I),I=1,10)
      READ(12,2000)BMVA,INFO
      READ(12,2021)NT,NE,NOC,NM,IGN,OUTTP
      READ(12,2021)NE3,NOC3,INTP,ESN,ISN,SIGN
      READ(12,2002)NLINE,NLCHS,NLCHM
      N1=ESN+IGN
      NWA=NE*(NE+2)
      NB=NT-ISN
      NBB=NB+1
      NSB=ESN+ISN
      N13F=N1*3
      NT3=N13F+3*ISN
      NGEN3=3*IGN
      NB3=3*NSB
      NBG3=ESN+ISN+SIGN
C
C
C
      WRITE(6,7)(TITLE(I),I=1,10)
 7    FORMAT(1X,10A8)
      WRITE(6,1299)
      WRITE(6,1299)
C
C
C     TYPES OF DATA INFORMATION IN THE STUDY AREA
C
C     1ST. LINE TYPES & Y012 - NLINE
C     2ND. TYPE & SELF LINE CHARGINGS 1/2Y012 - NLCHS
C     3RD. TYPE & MUTUAL LINE CHARGING 1/2Y012 - NLCHM
C     4TH. TYPE & LOAD COMPLEX UNBALANCE POWER PHASE SEQ- A,B, C
C                 INSIDE AND OUTSIDE OF STUDY IF ANY.
C
C
C
C     VVV(3,M2)- VVVT(3,M2) -NSE: NO. OF LINES IN THE STUDY AREA
C     STYP3 & YTYP3(ℓF SELF TYPES IN STUDY,3,3)-TYP3(NSE)
C     MTYP3(ℓF MUTUAL TYPES IN STUDY)
C
C     NT-TOTAL NO. OF SYSTEM NODES
```

```
C     ISN-NO. OF NODES INSIDE OF STUDY AREA
C     ESN-NO. OF NODES AT THE EDGE OF STUDY AREA
C     IGN-TOTAL NO. OF INTERNAL GENERATOR NODES
C     SIGN-TOTAL NO. OF INSIDE OF STUDY AREA INTERNAL GEN. NODES
C     NE-TOTAL NO. OF ELEMENTS
C     NM-NO. OF MUTUALLY COUPLED ELEMENTS
C     NOC-NO. OF COUPLINGS
C     INFO-OUTPUT INFORMATION: LINES I,P,Q.
C          0: NO
C          1: YES
C
      NB=NT-ISN
      N=NE
      NS1=NB+1
      NS2=N*(N+2)
      IN=(ISN+ESN+IGN)*3
      N1=ESN+IGN
      N13F=3*N1
C
C
C     ENTER THE TYPE OF ELEMENTS AND THEIR CORRESPONDING IMPEDANCES
C                      OUTSIDE OF STUDY
C
C
C
C     STYPO,1,2- CONTAINS 0,1,2 ELEMENTS OUTSIDE OF STUDY AREA
C                IN PU OHMS/MILES
C
      IIMUT=0
      WRITE(6,1400)
 1400 FORMAT('1',30X,'ELEMENTS OUTSIDE THE STUDY AREA')
      WRITE(6,1401)
 1401 FORMAT('0',30X,'SELF IMPEDANCES IN PU OHMS/MILES')
      WRITE(6,1403)
 1403 FORMAT('-',6X,'TYPE',10X,'R0    ',5X,'X0    ',6X,'R1    ',
     15X,'X1    ',5X,'R2    ',6X,'X2    ')
      DO 11 I=1,OUTTP
      STYP0(I)=(0.,0.)
      STYP1(I)=(0.,0.)
 11   STYP2(I)=(0.,0.)
      DO 12 I=1,3
 12   MTYP(I)=(0.,0.)
 13   READ(12,2023)ITYPE
      IF(ITYPE.EQ.99999)GO TO 998
      READ(12,2004)STYP0(ITYPE),STYP1(ITYPE),STYP2(ITYPE)
      WRITE(6,1404)ITYPE,STYP0(ITYPE),STYP1(ITYPE),STYP2(ITYPE)
 1404 FORMAT('0',I9,10X,E9.2,2X,E9.2,3X,E9.2,2X,E9.2,2X,E9.2,3X,E9.2)
      GO TO 13
C
C
```

```
C
C
C       FIND LOADS Z EQUIVALENT TO GROUND.
C
C       PP & QQ ARE 3-PHASE MW AND MVAR POWER @ LOAD
C       VOLT IS THE VOLTAGE MAGNITUDE @ LOAD
C
 998  CONTINUE
C
      READ(12,2005)ITYPE,PP,QQ,VOLT
      IF(ITYPE.EQ.99999)GO TO 15
      FAC=BMVA*VOLT*VOLT/(PP*PP+QQ*QQ)
      RR=PP*FA C
      XX=QQ*FA C
      STYP0(ITYPE)=CMPLX(RR,XX)
      STYP1(ITYPE)=STYP0(ITYPE)
      STYP2(ITYPE)=STYP0(ITYPE)
      WRITE(6,1404)ITYPE,STYP0(ITYPE),STYP1(ITYPE),STYP2(ITYPE)
      GO TO 998
 15   CONTINUE
      WRITE(6,1405)
 1405 FORMAT('-',37X,'MUTUAL IMPEDANCES IN PU OHMS/MILES')
      WRITE(6,1406)
 1406 FORMAT('0',6X,'TYPE',28X,'R0    ',5X,'X0    ')
 995  READ(12,2023)ITYPE
      IF(ITYPE.EQ.99999)GO TO 999
      IIMUT=IIMUT+1
      READ(12,2006)MTYP(ITYPE)
      WRITE(6,1407)ITYPE,MTYP(ITYPE)
 1407 FORMAT('0',I9,29X,E9.2,4X,E9.2)
      GO TO 995
C
C
C
C
C
C      ENTER THE TYPE OF ELEMENTS AND THEIR CORRESPONDING IMPEDANCES
C                       INSIDE OF STUDY
C
C
 999  CONTINUE
      IF(IIMUT.NE.0)GO TO 1000
      WRITE(6,1408)
 1408 FORMAT('0',8X,'0',29X,'0.00',4X,'0.00')
 1000 CONTINUE
      WRITE(6,1409)
 1409 FORMAT('-',30X,'ELEMENTS INSIDE OF THE STUDY AREA')
      WRITE(6,1410)
 1410 FORMAT('0',6X,'TYPE',26X,'Z012  IN PU OHMS/MILES  ')
 44   READ(12,2023)ITYPE
```

```
      IF(ITYPE.EQ.99999)GO TO 155
      CALL READ3(50,ITYPE,3,STYP3)
      WRITE(6,1411)ITYPE
 1411 FORMAT('0',I9)
      DO 1413 I=1,3
      WRITE(6,1412)(STYP3(ITYPE,I,J),J=1,3)
 1412 FORMAT('0',23X,3(E9.2,2X,E9.2,4X))
 1413 CONTINUE
      GO TO 44
C
 155  CONTINUE
      READ(12,2008)ITYPE,SA,SB,SC,VOLT
      IF(ITYPE.EQ.99999)GO TO 156
      FAC=VOLT*VOLT*BMVA/3.
      DO 1515 IK=1,3
      DO 1515 JK=1,3
      YY(IK,JK)=(0.,0.)
      AI(IK,JK)=(1.,0.)
 1515 A(IK,JK)=(1.,0.)
      YY(1,1)=CONJG(SA)/FA C
      YY(2,2)=CONJG(SB)/FA C
      YY(3,3)=CONJG(SC)/FA C
      AI(2,2)=(-.5,.866025)
      AI(3,3)=AI(2,2)
      A(2,3)=AI(2,2)
      A(3,2)=A(2,3)
      AI(2,3)=(-.5,-.866025)
      AI(3,2)=AI(2,3)
      A(2,2)=AI(3,2)
      A(3,3)=A(2,2)
      CALL MULT(3,3,3,3,3,3,AI,YY,OUTT)
      CALL MULT(3,3,3,3,3,3,OUTT,A,YY)
      DO 1516 IK=1,3
      DO 1516 JK=1,3
 1516 STYP3(ITYPE,IK,JK)=YY(IK,JK)/3.
      WRITE(6,1411)ITYPE
      DO 1517 IK=1,3
 1517 WRITE(6,1412)(STYP3(ITYPE,IK,JK),JK=1,3)
      GO TO 155
 156  CONTINUE
      IFLAG3=0
      WRITE(6,1415)
 1415 FORMAT('-',6X,'TYPE',40X,'MUTUAL IMPEDANCE MATRIX- 0,1,2',
     12X,'PU OHMS/MILES')
C
 55   READ(12,2023)MTYPE
      IF(MTYPE.EQ.99999)GO TO 1999
      WRITE(6,1422)MTYPE
      IFLAG3=1
      CALL READ3(10,MTYPE,6,MTYP3)
```

```
      DO 1419 I=1,6
 1419 WRITE(6,1420)(MTYP3(MTYPE,I,J),J=1,6)
      GO TO 55
 1420 FORMAT('0',5X,6(E9.1,1X,E9.1,2X))
 1422 FORMAT('0',I9)
C
C
C
 1999 CONTINUE
C
      IF(IFLAG3.NE.0)GO TO 2001
      WRITE(6,2003)
 2003 FORMAT('-',23X,'*** THERE IS NO MUTUAL COUPLING INSIDE OF',
     1' THE STUDY AREA')
 2001 CONTINUE
C
C
C
C
C
      IF(NM.EQ.0)NM=1
      CALL YBUSS0(300,20,86,8280,85,40,N,NB,NM,NS1,NS2,ESN,ISN,NODES,
     1ME,YBUS,WA,WK,ZT,YT,NOC,STYP0,MTYP,YBUS0)
      WRITE(6,900)
  900 FORMAT('-',5X,'CONNECTING NODES',3X,'TYPE',4X,'L, MILES',2X,
     1'POSITIVE SEQ. IMPEDANCES IN PU OHMS')
      WRITE(6,899)
  899 FORMAT('0',40X,'R1',9X,'X1')
      CALL YBUSS1(85,NB,ESN,ISN,STYP1,YBUS1)
      WRITE(6,901)
  901 FORMAT('-',5X,'CONNECTING NODES',3X,'TYPE',8X,
     1'NEGATIVE SEQ. IMPEDANCES IN PU OHMS')
      WRITE(6,891)
  891 FORMAT('0',40X,'R2',9X,'X2')
      CALL YBUSS1(85,NB,ESN,ISN,STYP2,YBUS2)
C
C
C     REDUCTION PROCEDURE. RETAINS THE IST N1=ESN+IGN NODES
C
C
C
      K=NB
   43 CALL KRON3(85,NB,K,ITEST,YBUS0)
      IF (ITEST.EQ.1)GO TO 4444
      K=K-1
      IF(K.GT.N1)GO TO 43
      K=NB
   45 CALL KRON3(85,NB,K,ITEST,YBUS1)
      IF (ITEST.EQ.1)GO TO 4444
      K=K-1
```

```
      IF(K.GT.N1)GO TO 45
      K=NB
 46   CALL KRON3(85,NB,K,ITEST,YBUS2)
      IF (ITEST.EQ.1)GO TO 4444
      K=K-1
      IF(K.GT.N1)GO TO 46
      DO 14 I=1,N1
      DO 14 J=1,N1
      YBUS00(I,J)=YBUS0(I,J)
      YBUS11(I,J)=YBUS1(I,J)
 14   YBUS22(I,J)=YBUS2(I,J)
C
C     NEW YBUS0 YBUS1 YBUS2 ARE NOW CONSTRUCTED. BUILD YBUS012
C     FROM THESE (Y3F1).
C
      CALL YBUS3F(65,195,N13F,N1,YBUS00,YBUS11,YBUS22,Y3F1)
C
C     MAKE ROOM FOR THE INSIDE OF STUDY NODES.
C
      M1=ESN
      M2=M1+ISN
      III=ESN+ISN+SIGN
      M3=N1+ISN
      M13F=3*M1
      M23F=3*M2
      M33F=3*M3
      IGN3=3*IGN
      IS1=M13F+1
      IS2=M23F+1
      DO 26 I=IS1,M33F
      DO 26 J=1,M33F
      Y3F2(I,J)=(0.,0.)
 26   Y3F2(J,I)=(0.,0.)
      DO 27 I=1,M13F
      DO 27 J=1,M13F
 27   Y3F2(I,J)=Y3F1(I,J)
      II=M13F
      DO 28 I=IS2,M33F
      II=II+1
      JJ=0
      DO 28 J=1,M13F
      JJ=JJ+1
      Y3F2(I,J)=Y3F1(II,JJ)
 28   Y3F2(J,I)=Y3F1(JJ,II)
      II=M13F
      DO 29 I=IS2,M33F
      II=II+1
      JJ=M13F
      DO 29 J=IS2,M33F
      JJ=JJ+1
```

```
 29   Y3F2(I,J)=Y3F1(II,JJ)
C
C
C     Y3F2 IS NOW CONSTRUCTED.
C     START READING INSIDE THE STUDY DATA.
C
C
C
C     ENTER THE MUTUALLY COUPLED ELEMENTS
C
      NM=0
      MFLAG=0
C
C     READ THE MUTUAL IMPEDANCE MATRICES AND BUILD THE MUTUAL Z MATRIX
C     THEN FIND MUTUAL Y MATRIX
C
C     ZMUT- PRIMITIVE MATRIX FOR MUTUAL COUPLING. 3*NME BY 3*NME
C     YMUT- ZMUT INVERSE
C     ME3- STORES THE MUTUAL ELEMENTS ES & EM. (NM,2)
C     NODE3- STORES THE NODES OF ES & EM. (NME,2)
C     NME- NO. OF ELEMENTS COUPLED TOGETHER. NM- NO. OF COUPLINGS
C
      READ(12,2023)NME
      NB=M3
      INME=NME*3
      IN=NB*3
 10   READ(12,2012)ES,R,S,EM,P,Q,MTYPE,ILEN
      IF(ES.EQ.99999)GO TO 1100
      MFLAG=1
      NM=NM+1
      IS=NM*3-2
      IE=IS+5
      II=0
      DO 313 I=IS,IE
      II=II+1
      JJ=0
      DO 313 J=IS,IE
      JJ=JJ+1
 313  ZMUT(I,J)=MTYP3(MTYPE,II,JJ)*10000.
      NODE3(ES,1)=R
      NODE3(ES,2)=S
      NODE3(EM,1)=P
      NODE3(EM,2)=Q
      ME3(NM,1)=ES
      ME3(NM,2)=EM
      IMLEN(NM)=ILEN
      MTP(NM)=MTYPE
      GO TO 10
 1100 CONTINUE
      IF(MFLAG.EQ.0)GO TO 1120
```

```
C
C
C
      CALL UNITY(63,INME,YMUT)
      CALL LEQ2C(ZMUT,INME,63,YMUT,INME,63,0,WA,WK,IER)
      NMC=NM*3+3
      DO 4411 IT=1,NM C
      DO 4411 JT=1,NM C
 4411 YMTYP3(IT,JT)=YMUT(IT,JT)*10000.
C     ENTER THE UNCOUPLED ELEMENTS
C
      NSE=0
 34   READ(12,2010)ES,P,Q,ITYPE,ILEN
      IF(ES.EQ.99999)GO TO 1002
      ES=ES+NME
      CALL EQUAL3(50,ITYPE,3,STYP3,ZSS)
      IILEN(ES)=ILEN
      IF(P.EQ.0)GO TO 121
      CALL UNITY(3,3,YSS)
      CALL LEQ2C(ZSS,3,3,YSS,3,3,0,WA,WK,IER)
      DO 35 I=1,3
      DO 35 J=1,3
 35   YTYP3(ITYPE,I,J)=YSS(I,J)
      DO 7777 I=1,3
      DO 7777 J=1,3
 7777 YSS(I,J)=YSS(I,J)/ILEN
      CALL NEG(3,YSS,NYSS)
      CALL ADD(240,P,Q,IN,NYSS,Y3F2)
      CALL ADD(240;P,P,IN,YSS,Y3F2)
      CALL ADD(240,Q,Q,IN,YSS,Y3F2)
      CALL ADD(240,Q,P,IN,NYSS,Y3F2)
      NSE=NSE+1
      NODE3(ES,1)=P
      NODE3(ES,2)=Q
      TYP3(ES)=ITYPE
      GO TO 34
 121  CONTINUE
      DO 3349 IIZ=1,3
      DO 3349 JJZ=1,3
 3349 ZSS(IIZ,JJZ)=ZSS(IIZ,JJZ)*ILEN
      CALL ADD(240,Q,Q,IN,ZSS,Y3F2)
      GO TO 34
C
 1002 CONTINUE
C
C
C     THREE-PHASE MUTUAL CONSIDERATION
C
      DO 203 I=1,NM
      ES=ME3(I,1)
```

```
      EM=ME3(I,2)
      R=NODE3(ES,1)
      S=NODE3(ES,2)
      P=NODE3(EM,1)
      Q=NODE3(EM,2)
      ILEN=IMLEN(I)
      CALL PART(63,3,3,NMC,ES,ES,YRS,YMTYP3)
      CALL PART(63,3,3,NMC,ES,EM,YM1,YMTYP3)
      CALL PART(63,3,3,NMC,EM,ES,YM2,YMTYP3)
      CALL PART(63,3,3,NMC,EM,EM,YPQ,YMTYP3)
      DO 4422 IT=1,3
      DO 4422 JT=1,3
      YRS(IT,JT)=YRS(IT,JT)/ILEN
      YM1(IT,JT)=YM1(IT,JT)/ILEN
      YM2(IT,JT)=YM2(IT,JT)/ILEN
 4422 YPQ(IT,JT)=YPQ(IT,JT)/ILEN
      CALL NEG(3,YPQ,NYPQ)
      CALL NEG(3,YM1,NYM1)
      CALL NEG(3,YM2,NYM2)
      CALL NEG(3,YRS,NYRS)
      CALL ADD(240,P,P,IN,YPQ,Y3F2)
      CALL ADD(240,Q,Q,IN,YPQ,Y3F2)
      CALL ADD(240,R,R,IN,YRS,Y3F2)
      CALL ADD(240,S,S,IN,YRS,Y3F2)
      CALL ADD(240,Q,S,IN,YM2,Y3F2)
      CALL ADD(240,S,Q,IN,YM1,Y3F2)
      CALL ADD(240,P,R,IN,YM2,Y3F2)
      CALL ADD(240,R,P,IN,YM1,Y3F2)
      CALL ADD(240,P,Q,IN,NYPQ,Y3F2)
      CALL ADD(240,Q,P,IN,NYPQ,Y3F2)
      CALL ADD(240,Q,R,IN,NYM2,Y3F2)
      CALL ADD(240,R,Q,IN,NYM1,Y3F2)
      CALL ADD(240,S,P,IN,NYM1,Y3F2)
      CALL ADD(240,P,S,IN,NYM2,Y3F2)
      CALL ADD(240,R,S,IN,NYRS,Y3F2)
  203 CALL ADD(240,S,R,IN,NYRS,Y3F2)
C
 1120 CONTINUE
      DO 4433 I=1,IGN3
 4433 VG(I,1)=(0.,0.)
      DO 4434 I=1,IGN
      READ(12,2013)VGG(I)
      II=I*3-1
 4434 VG(II,1)=VGG(I)
C
C
      DO 1121 I=1,III
 1121 READ(12,2014)IK,NAME(IK)
C     PARTITION Y3F2 TO FIND Y1 & Y2
C
```

```
C
C
      MX=M23F+1
      II=0
      DO 801 I=1,M23F
      II=II+1
      JJ=0
      DO 801 J=1,M23F
      JJ=JJ+1
 801  Y1V(II,JJ)=Y3F2(I,J)
      II=0
      DO 802 I=1,M23F
      II=II+1
      JJ=0
      DO 802 J=MX,M33F
      JJ=JJ+1
 802  Y2V(II,JJ)=Y3F2(I,J)
C
      CALL UNITY(90,M23F,Y1VI)
      CALL LEQ2C(Y1V,M23F,90,Y1VI,M23F,90,0,WA,WK,IER)
      CALL MULT(90,90,150,M23F,M23F,IGN3,Y1VI,Y2V,YOUT3)
      CALL MULT(90,150,1,M23F,IGN3,1,YOUT3,VG,V)
      DO 803 I=1,M23F
 803  V(I,1)=-V(I,1)
      CALL POLAR(M23F,V,MAG,ANG)
      JS=-2
      JE=0
      DO 805 I=1,M2
      WRITE(6,1299)
      IS=0
      JS=JS+3
      JE=JE+3
      WRITE(6,1099)I,NAME(I)
 1099  FORMAT('-',15X,'NODE',I2,1X,'(',A6,')',
     1'SEQUENCE VOLTAGES: 0,1,2')
      DO 804 J=JS,JE
      IS=IS+1
      WRITE(6,902)MAG(J),ANG(J)
      VVV(IS,I)=V(J,1)
 804  VV(IS)=V(J,1)
      WRITE(6,1199)
      CALL TRANSF(VV,1,VVT)
      DO 907 IX=1,3
 907  VVVT(IX,I)=VVT(IX)
 805  CONTINUE
 1199 FORMAT('-',50X,'PHASE VOLTAGES: A,B,C')
 902  FORMAT('0',5X,'MAG=',F8.6,'/__',F7.2)
 1299 FORMAT('-')
      WRITE(6,5980)
 5980 FORMAT('1')
```

```
C
      IF(INFO.EQ.0)GO TO 9000
      WRITE(6,5981)
 5981 FORMAT('-',10X,'LINE',12X,'I 0,1,2(PU)',10X,'V 0,1,2(PU)',
     112X,'P A,B,C(MW)',2X,'Q A,B,C(MVAR)')
C
C
C     COMPUTATIONS OF CURRENT AND POWER FLOWS
C
      DO 3001 J=1,NSE
      I=J+NME
      ILEN=IILEN(I)
      P=NODE3(I,1)
      Q=NODE3(I,2)
      ITYPE=TYP3(I)
      CALL EQUAL3(50,ITYPE,3,YTYP3,YSS)
      IZ=ITYPE+NLINE
      CALL EQUAL3(50,IZ,3,STYP3,NYSS)
      WRITE(6,7000)P,Q,NAME(P),NAME(Q)
 7000 FORMAT('-',1X,I2,'-',I2,2X,'(',A6,'- ',A6,')')
      DO 3333 IV=1,3
      DO 3333 JV=1,3
      YSS(IV,JV)=YSS(IV,JV)/ILEN
 3333 NYSS(IV,JV)=NYSS(IV,JV)*ILEN
      CALL CURRO(M2,P,Q,NAME,VVV,VVVT,YSS,NYSS)
      WRITE(6,7000)Q,P,NAME(Q),NAME(P)
      CALL CURRO(M2,Q,P,NAME,VVV,VVVT,YSS,NYSS)
 3001 CONTINUE
C
C
C
C     DOUBLE-CKT LINES CURRENT & POWER FLOWS COMPUTATION PROCEDURE
C
      DO 8000 I=1,NM
      ILEN=IMLEN(I)
      ES=ME3(I,1)
      EM=ME3(I,2)
      R=NODE3(ES,1)
      S=NODE3(ES,2)
      P=NODE3(EM,1)
      Q=NODE3(EM,2)
      MTYPE=MTP(I)
      CALL PART(63,3,3,NMC,ES,ES,YRS,YMTYP3)
      CALL PART(63,3,3,NMC,ES,EM,YM1,YMTYP3)
      CALL PART(63,3,3,NMC,EM,ES,YM2,YMTYP3)
      CALL PART(63,3,3,NMC,EM,EM,YPQ,YMTYP3)
      DO 8111 IT=1,3
      DO 8111 JT=1,3
      YRS(IT,JT)=YRS(IT,JT)/ILEN
      YM1(IT,JT)=YM1(IT,JT)/ILEN
```

```
      YM2(IT,JT)=YM2(IT,JT)/ILEN
 8111 YPQ(IT,JT)=YPQ(IT,JT)/ILEN
      INDEX=I+NLINE+NLCHS
      CALL CURR3(30,R,S,P,Q,M2,ILEN,MTYPE,NAME,VVV,VVVT,YRS,YM1,YM2,
     1YPQ,INDEX,STYP3)
 8000 CALL CURR3(30,S,R,Q,P,M2,ILEN,MTYPE,NAME,VVV,VVVT,YRS,YM1,YM2,
     1YPQ,INDEX,STYP3)
 4444 CONTINUE
C
C
C
C     PROCEDURES TO COMPUTE CURRENT AND POWER UNBALANCES @ THE GEN-
C     ERATORS INSIDE OF STUDY AREA.
C
C
 9000 CONTINUE
      WRITE(6,5980)
      WRITE(6,7778)
 7778 FORMAT('0',23X,'CONTINUOUS CURRENT AND POWER UNBALANCE AT THE',
     1' HIGH VOLTAGE BUS OF THE GENERATORS')
      IJ=0
      DO 7779 IZ=1,SIGN
      READ(12,2015)LVBUS,HVBUS,ZT1,ZTM2
      IS=3*HVBUS-3
      DO 8100 I=1,3
      IJ=IJ+1
      IS=IS+1
      GVOLT(I)=VG(IJ,1)
 8100 HVOLT(I)=V(IS,1)
      YT1=1./ZT1
      YTM2=1./ZTM2
      WRITE(6,8006)LVBUS,NAME(LVBUS)
 8006 FORMAT('0',15X,'NODE',I3,1X,'(',A6,')')
      WRITE(6,8007)
 8007 FORMAT('-',22X,'I 0,1,2(PU)',10X,'P A,B,C(MW)',2X,
     1'Q A,B,C(MVAR)')
      CALL GENI(GVOLT,HVOLT,YT1,YTM2,IGEN,MAGI,ANGI)
      CALL MULT(3,3,1,3,3,1,A,IGEN,IGENT)
      DO 8999 IT=1,3
 8999 HVOLTT(IT)=VVVT(IT,HVBUS)
      SS(1)=HVOLTT(1)*CONJG(IGENT(1))*BMVA/3.
      SS(2)=HVOLTT(2)*CONJG(IGENT(2))*BMVA/3.
      SS(3)=HVOLTT(3)*CONJG(IGENT(3))*BMVA/3.
      DO 8008 I=1,3
 8008 WRITE(6,8009)MAGI(I),ANGI(I),SS(I)
 8009 FORMAT('0',22X,F8.4,1X,'/__',F7.2,3X,F9.2,4X,F9.2)
 7779 CONTINUE
 2999 FORMAT(10A8)
 2000 FORMAT(F10.2,I5)
 2021 FORMAT(6I5)
```

```
 2002 FORMAT(3I5)
 2023 FORMAT(I5)
 2004 FORMAT(6E10.3)
 2005 FORMAT(I5,3F10.5)
 2006 FORMAT(2F10.7)
 2008 FORMAT(I5,6F10.3,F10.6)
 2010 FORMAT(4I5,F10.2)
 2012 FORMAT(7I5,F10.2)
 2013 FORMAT(2F10.6)
 2014 FORMAT(I5,A6)
 2015 FORMAT(2I5,4F10.5)
      STOP
      END
C
C
C
C     SUBROUTINE FOR POSITIVE OR NEGATIVE SEQUENCE YBUS
C
      SUBROUTINE YBUSS1(IDIM,NB,ESN,ISN,STYP,YBUS)
      INTEGER ESN,P,M
      REAL ILEN
      COMPLEX STYP(1),YBUS(IDIM,IDIM),Y,ZZ
      DO 100 I=1,NB
      DO 100 J=1,NB
 100  YBUS(I,J)=(0.,0.)
 10   READ(12,2011)P,M,ITYPE,ILEN
      IF(P.EQ.99999) GO TO 400
      IF(P.NE.0)GO TO 889
      ZZ=STYP(ITYPE)/ILEN
      GO TO 900
 889  ZZ=STYP(ITYPE)*ILEN
 900  IF(CABS(ZZ).GE.10.)GO TO 111
      WRITE(6,901)P,M,ITYPE,ILEN,ZZ
 901  FORMAT(' ',10X,I2,'-',I2,9X,I3,4X,F6.2,2X,F7.4,5X,F7.4)
      GO TO 333
 111  WRITE(6,222)P,M,ITYPE,ILEN,ZZ
 222  FORMAT(' ',10X,I2,'-',I2,9X,I3,4X,F6.2,2X,F7.4,5X,F7.0)
 333  CONTINUE
      IF(P.GT.ESN)P=P-ISN
      IF(M.GT.ESN)M=M-ISN
      IF(CABS(ZZ).EQ.0.)GO TO 112
      Y=1./ZZ
      GO TO 113
 112  Y=(0.,1000.)
 113  IF(P.EQ.0)GO TO 103
      YBUS(P,P)=YBUS(P,P)+Y
      YBUS(P,M)=YBUS(P,M)-Y
      YBUS(M,P)=YBUS(M,P)-Y
 103  YBUS(M,M)=YBUS(M,M)+Y
      GO TO 10
```

```
 400  CONTINUE
      RETURN
 2011 FORMAT(3I5,F10.2)
      END
C
C
C
C
C
C
C
C     SUBROUTINE TO MULTIPLY (K1,K2) * (K2,K3)
      SUBROUTINE MULT(ID1,ID2,ID3,K1,K2,K3,MAT1,MAT2,OUT)
      COMPLEX MAT1(ID1,ID2),MAT2(ID2,ID3),OUT(ID1,ID3),SUM
      INTEGER L
      DO 95 I=1,K1
      DO 95 L=1,K3
      SUM=(0.,0.)
      DO 94 J=1,K2
  94  SUM=SUM+MAT1(I,J)*MAT2(J,L)
      OUT(I,L)=SUM
  95  CONTINUE
      RETURN
      END
C
C
C
C
C
C     SUBROUTINE FOR ZERO SEQUENCE YBUS
      SUBROUTINE YBUSSO(I1,I2,I3,I4,I5,I6,N,NB,NME,NS1,NS2,ESN,ISN,
     1NODES,ME,YBUS,WA,WK,ZT,YT,NOC,STYP,MTYP,YBUSO)
      INTEGER P,Q,R,S,EM,ES,NODES(I1,2),ME(I2,2),ES1,ES2,SI1,SI2,SM,ESN
      COMPLEX ZS,ZM,YBUS(I3,I3),WA(I4),YM
      COMPLEX YBUSO(I5,I5),STYP(1),MTYP(1)
      COMPLEX ZT(I6,I6),YT(I6,I6),ZS1,ZS2
      REAL WK(1),ILEN
C
C     N(NE)- OF ELEMENTS.  NB= OF BUSES.  NM- OF MUTUAL ELEMENTS
C     NI- OF BUSES INCLUDING THE REFERENCE BUS (GROUND BUS)
C      WA-(N,N+2). WK-(N)
C     YBUS-INDEFINITE ADMITTANCE MATRIX (NB+1,NB+1).
C     YBUSO-DEFINITE ADMITTANCE MATRIX (NB,NB)
C     NODES-MATRIX FOR THE NODES OF N ELEMENTS (N,2)
C     ZT & YT-PRIMITIVE IMPEDANCE AND ADMITTANCE MATRICES (NM,NM)
C     ME-CONTAINS NM MUTUAL ELEMENTS (NOC,2)
C     ZBUS-ZEO SEQUENCE ZBUS (NB,NB)
C     NME-TOTAL NO. OF ELEMENTS MUTUALLY COUPLED
C     NOC-NO. OF COUPLINGS
C     ZT-A SUBMATRIX IN PRIMITIVE IMPEDANCE MATRIX WHICH CONTAINS
```

```
C         THE MUTUAL ELEMENTS IMPEDANCES (NME,NME)
C      YT-INVERSE OF ZT (NME,NME)
       IF(NOC.EQ.0)NME=0
       NR=N-NME
       NI=NB+1
       DO 50 I=1,NI
       DO 50 J=1,NI
 50    YBUS(I,J)=(0.,0.)
       NE=0
       NM=0
       WRITE(6,972)
 972   FORMAT('1',20X,'ZERO SEQ. IMPEDANCES IN PU OHMS')
       WRITE(6,12)
 12    FORMAT('-',2X,'ES',3X,'NODES',1X,'TYPE',2X,'L, MILES',2X,'RSO',
      16X,'XSO',5X,
      2'EM',3X,'NODES',1X,'TYPE',2X,'RSO',5X,'XSO',5X,'RM',6X,'XM')
C
C
C
C        ENTER THE COUPLED ELEMENTS FIRST.
C
C
C
C
C        TAKE CARE OF THE COUPLINGS
         IF(NOC.EQ.0)GO TO 117
         DO 112 I=1,NO C
         READ(12,2009)ES1,P,Q,SI1,ES2,R,S,SI2,SM,ILEN
         ZS1=STYP(SI1)*ILEN
         ZS2=STYP(SI2)*ILEN
         ZM=MTYP(SM)*ILEN
        WRITE(6,13)ES1,P,Q,SI1,ILEN,ZS1,ES2,R,S,SI2,ZS2,ZM
 13     FORMAT('0',2X,I2,3X,I2,'-',I2,1X,I3,4X,F6.2,1X,F7.4,2X,F7.4,
      11X,I2,3X,I2,'-',I2,1X,I3,4X,F7.4,1X,F7.4,1X,F7.4,1X,F7.4)
        IF(P.GT.ESN)P=P-ISN
        IF(Q.GT.ESN)Q=Q-ISN
        IF(R.GT.ESN)R=R-ISN
        IF(S.GT.ESN)S=S-ISN
        IF(P.EQ.0)P=NB+1
        IF(Q.EQ.0)Q=NB+1
        IF(R.EQ.0)R=NB+1
        IF(S.EQ.0)S=NB+1
         NODES(ES1,1)=P
         NODES(ES1,2)=Q
         NODES(ES2,1)=R
         NODES(ES2,2)=S
         ME(I,1)=ES1
         ME(I,2)=ES2
         ZT(ES1,ES1)=ZS1
         ZT(ES1,ES2)=ZM
```

```
      ZT(ES2,ES1)=ZM
 112  ZT(ES2,ES2)=ZS2
      CALL UNITY(40,NME,YT)
      CALL LEQ2C(ZT,NME,40,YT,NME,40,0,WA,WK,IER)
C
 117  CONTINUE
C
C
C     READ THE SELF DATA
      DO 201 I=1,NR
      READ(12,2010)ES1,P,Q,SI1,ILEN
      IF(P.NE.0)GO TO 889
      ZS=STYP(SI1)/ILEN
      GO TO 900
 889  ZS=STYP(SI1)*ILEN
 900  ZS2=(0.,0.)
      ZM=(0.,0.)
      ES2=0
      R=0
      S=0
      IF(ABS(AIMAG(ZS)).GE.10.)GO TO 293
     WRITE(6,13)ES1,P,Q,SI1,ILEN,ZS,ES2,R,S,SI2,ZS2,ZM
      GO TO 763
 293 WRITE(6,180)ES1,P,Q,SI1,ILEN,ZS,ES2,R,S,SI2,ZS2,ZM
 763 CONTINUE
 180 FORMAT('0',2X,I2,3X,I2,'-',I2,1X,I3,4X,F6.2,1X,F7.4,2X,F6.0,2X,
    1I2,3X,I2,'-',I2,1X,I3,4X,F7.4,1X,F7.4,1X,F7.4,1X,F7.4)
     IF(P.GT.ESN)P=P-ISN
     IF(Q.GT.ESN)Q=Q-ISN
     IF(P.EQ.0)P=NB+1
     IF(Q.EQ.0)Q=NB+1
      NODES(ES1,1)=P
      NODES(ES1,2)=Q
      ZS=1./ZS
      YBUS(P,P)=YBUS(P,P)+ZS
      YBUS(P,Q)=YBUS(P,Q)-ZS
      YBUS(Q,P)=YBUS(Q,P)-ZS
 201  YBUS(Q,Q)=YBUS(Q,Q)+ZS
C
C
C
C
C     MUTUAL CONSIDERATIONS
C
      IF(NOC.EQ.0)GO TO 218
      DO 200 I=1,NO C
      ES1=ME(I,1)
      ES2=ME(I,2)
      YM=YT(ES1,ES2)
      P=NODES(ES1,1)
```

```
      Q=NODES(ES1,2)
      R=NODES(ES2,1)
      S=NODES(ES2,2)
      ZS1=YT(ES1,ES1)
      ZS2=YT(ES2,ES2)
       YBUS(P,P)=YBUS(P,P)+ZS1
       YBUS(P,Q)=YBUS(P,Q)-ZS1
       YBUS(Q,P)=YBUS(Q,P)-ZS1
       YBUS(Q,Q)=YBUS(Q,Q)+ZS1
       YBUS(R,R)=YBUS(R,R)+ZS2
       YBUS(R,S)=YBUS(R,S)-ZS2
       YBUS(S,R)=YBUS(S,R)-ZS2
       YBUS(S,S)=YBUS(S,S)+ZS2
      YBUS(R,P)=YBUS(R,P)+YM
      YBUS(P,R)=YBUS(P,R)+YM
      YBUS(S,Q)=YBUS(S,Q)+YM
      YBUS(Q,S)=YBUS(Q,S)+YM
      YBUS(R,Q)=YBUS(R,Q)-YM
      YBUS(Q,R)=YBUS(Q,R)-YM
      YBUS(S,P)=YBUS(S,P)-YM
      YBUS(P,S)=YBUS(P,S)-YM
 200  CONTINUE
 218  CONTINUE
      DO 500 I=1,NB
      DO 500 J=1,NB
 500  YBUSO(I,J)=YBUS(I,J)
 2009 FORMAT(9I5,F10.2)
 2010 FORMAT(4I5,F10.2)
      RETURN
      END
C
C
C
      SUBROUTINE UNITY(IDIM,N,B)
      COMPLEX B(IDIM,IDIM)
      DO 100 I=1,N
      DO 100 J=1,N
      IF(I.EQ.J)B(I,J)=(1.,0.)
      IF(I.NE.J)B(I,J)=(0.,0.)
 100  CONTINUE
      RETURN
      END
C
C
C
C     SUBROUTINE FOR THREE-PHASE YBUS 0,1,2
      SUBROUTINE YBUS3F(ID1,ID2,IN,NB,YBUSO,YBUS1,YBUS2,Y3F)
      COMPLEX YBUSO(ID1,ID1),YBUS1(ID1,ID1),YBUS2(ID1,ID1),Y3F(ID2,ID2)
      DO 123 I=1,IN
      DO 123 J=1,IN
```

```
 123  Y3F(I,J)=(0.,0.)
      IIN=IN-2
      IJN=IN-1
      DO 700 I=1,IIN,3
      II=(I+2)/3
      DO 700 J=1,IIN,3
      JJ=(J+2)/3
 700  Y3F(I,J)=YBUS0(II,JJ)
      DO 800 I=2,IJN,3
      II=(I+1)/3
      DO 800 J=2,IJN,3
      JJ=(J+1)/3
      Y3F(I,J)=YBUS1(II,JJ)
      IZ=I+1
      JZ=J+1
 800  Y3F(IZ,JZ)=YBUS2(II,JJ)
      RETURN
      END
C
C
C
C     SUBROUTINE TO BE USED TO BUILD THE YBUS
      SUBROUTINE ADD(IDIM,R,S,ISIZE,YIN,YBUS)
      INTEGER R,S
      COMPLEX YIN(3,3),YBUS(IDIM,IDIM)
      IS=3*R-3
      DO 100 I=1,3
      IS=IS+1
      JS=3*S-3
      DO 100 J=1,3
      JS=JS+1
 100  YBUS(IS,JS)=YBUS(IS,JS)+YIN(I,J)
      RETURN
      END
C
C
C
C
C     SUBROUTINE FOR BUILDING A MATRIX
      SUBROUTINE BUILD(R,S,ZIN,ZMUT)
      COMPLEX ZIN(3,3),ZMUT(6,6)
      INTEGER R,S
      IS=3*R-3
      DO 100 I=1,3
      IS=IS+1
      JS=3*S-3
      DO 100 J=1,3
      JS=JS+1
 100  ZMUT(IS,JS)=ZIN(I,J)
      RETURN
```

```
      END
C
C
C
C     SUBROUTINE TO NEGATE A MATRIX
      SUBROUTINE NEG(N,W,NW)
      COMPLEX W(N,N),NW(N,N)
      DO 100 I=1,N
      DO 100 J=1,N
 100  NW(I,J)=-W(I,J)
      RETURN
      END
C
C
C
C     SUBROUTINE FOR PARTITIONING THE MATRIX
      SUBROUTINE PART(IDIM,N,M,NMC,N1,N2,YIN,YMUT)
      INTEGER NN(2),IP(1),IQ(1),JP(1),JQ(1)
      COMPLEX YIN(N,M),YMUT(IDIM,IDIM)
      NN(1)=N1
      NN(2)=N2
      NR=N/3
      NC=M/3
      DO 200 I=1,NR
      IP(I)=3*NN(I)-2
      IQ(I)=IP(I)+2
 200  CONTINUE
      L=NR
      DO 300 I=1,N C
      L=L+1
      JP(I)=3*NN(L)-2
      JQ(I)=JP(I)+2
 300  CONTINUE
      I=0
      DO 410 IT=1,NR
      IS=IP(IT)
      IE=IQ(IT)
      DO 410 II=IS,IE
      I=I+1
      J=0
      DO 410 JT=1,N C
      JS=JP(JT)
      JE=JQ(JT)
      DO 410 JJ=JS,JE
      J=J+1
      YIN(I,J)=YMUT(II,JJ)
 410  CONTINUE
      RETURN
      END
C
```

```
C
      SUBROUTINE READ3(IDIM,NTYPE,N1,MAT)
      COMPLEX MAT(IDIM,N1,N1)
      DO 100 I=1,N1
 100  READ(12,2007)(MAT(NTYPE,I,J),J=1,N1)
 2007 FORMAT(6E10.3)
      RETURN
      END
C
C
C
      SUBROUTINE EQUAL3(IDIM,MTYPE,N1,MOLD,MNEW)
      COMPLEX MOLD(IDIM,N1,N1),MNEW(N1,N1)
      DO 100 I=1,N1
      DO 100 J=1,N1
 100  MNEW(I,J)=MOLD(MTYPE,I,J)
      RETURN
      END
C
C
C
C     THIS SUBROUTINE CONVERTS RECTANGULAR COORDINATES TO POLAR.
C
      SUBROUTINE POLAR(M,INPUT,MAG,ANG)
      REAL MAG(M),ANG(M)
      COMPLEX INPUT(M)
      PI=3.1415926
      DO 200 I=1,M
      RI=REAL(INPUT(I))
      AI=AIMAG(INPUT(I))
      MAG(I)=SQRT(RI**2+AI**2)
      IF(RI.EQ.0.)GO TO 49
      ANG(I)=ATAN2(AI,RI)
      ANG(I)=ANG(I)*180./PI
      GO TO 200
 49   IF(AI.EQ.0.)ANG(I)=0.
      IF(AI.NE.0.)ANG(I)=90.
 200  CONTINUE
      RETURN
      END
C
C
C
C     SUBROUTINE FOR 0,1,2 TO A,B,C TRANSFORMATION
C
      SUBROUTINE TRANSF(VV,IFLAG,VVT)
      REAL MAGP(3),ANGP(3)
      COMPLEX A(3,3),VV(3),VVT(3)
      DO 100 I=1,3
      A(I,1)=(1.,0.)
```

```
 100  A(1,I)=(1.,0.)
      A(2,2)=(-.5,-.866)
      A(3,3)=A(2,2)
      A(2,3)=(-.5,.866)
      A(3,2)=A(2,3)
      CALL MULT(3,3,1,3,3,1,A,VV,VVT)
      CALL POLAR(3,VVT,MAGP,ANGP)
      IF(IFLAG.EQ.0)GO TO 300
      DO 200 I=1,3
 200  WRITE(6,999)MAGP(I),ANGP(I)
 999  FORMAT('0',50X,'MAG=',F8.6,'/__',F7.2)
 300  RETURN
      END
C
C
C
C
C
C     SUBROUTINE TO COMPUTE CURRENT FLOWS FROM P TO Q
C
      SUBROUTINE CURRO(M2,P,Q,NAME,VVV,VVVT,YSS,NYSS)
      INTEGER P,Q,M2
      REAL MAGI(3),MAGV(3),ANGI(3),ANGV(3)
      COMPLEX VVV(3,M2),VVVT(3,M2),ILINE(3),ILENT(3),POWER(3)
      COMPLEX YSS(3,3),NYSS(3,3),DV(3),OUT1(3),OUT2(3),VL(3)
      REAL*8 NAME(1)
      DO 3002 II=1,3
 3002 DV(II)=VVV(II,P)-VVV(II,Q)
      DO 3003 K=1,3
 3003 VL(K)=VVV(K,P)
      CALL MULT(3,3,1,3,3,1,NYSS,VL,OUT1)
      CALL MULT(3,3,1,3,3,1,YSS,DV,OUT2)
      DO 3004 IX=1,3
 3004 ILINE(IX)=OUT1(IX)+OUT2(IX)
C
      CALL POWERO(P,Q,M2,ILINE,VL,VVVT,NAME)
C
      RETURN
      END
C
C
C     THIS SUBROUTINE COMPUTES POWER FLOW
C
      SUBROUTINE POWERO(P,Q,M2,ILINE,VL,VVVT,NAME)
      INTEGER P,Q,M2
      REAL MAGI(3),MAGV(3),ANGI(3),ANGV(3)
      COMPLEX VVVT(3,M2),ILINE(3),ILENT(3),POWER(3)
      COMPLEX YSS(3,3),NYSS(3,3),DV(3),OUT1(3),OUT2(3),VL(3)
      REAL*8 NAME(1)
      COMMON BMVA
```

```
      CALL POLAR(3,ILINE,MAGI,ANGI)
      CALL POLAR(3,VL,MAGV,ANGV)
      CALL TRANSF(ILINE,0,ILENT)
      DO 3005 K=1,3
      ILENT(K)=CONJG(ILENT(K))
 3005 POWER(K)=VVVT(K,P)*ILENT(K)*BMVA/3.
      DO 7001 IX=1,3
 7001 WRITE(6,7002)MAGI(IX),ANGI(IX),MAGV(IX),ANGV(IX),POWER(IX)
 7002 FORMAT('0',25X,F8.4,1X,'/__',F7.2,1X,F8.4,1X,'/__',F7.2,3X,
     1F9.2,4X,F9.2)
      RETURN
      END
C
C
C
C     SUBROUTINE TO COMPUTE DOUBLE-CKT LINES CURRENT FLOWS
      SUBROUTINE CURR3(IDIM,R,S,P,Q,M2,ILEN,MTYPE,NAME,VVV,VVVT,YRS,YM1,
     1YM2,YPQ,INDEX,STYP3)
      INTEGER CKT,P,Q,R,S,M2
      COMPLEX VVV(3,IDIM),VVVT(3,IDIM),YRS(3,3),YM1(3,3),YM2(3,3)
      REAL ILEN
      COMPLEX YPQ(3,3),DELV1(3),DELV2(3),V1(3),V2(3),YC1(3,3)
      COMPLEX YC2(3,3),OUT1(3),OUT2(3),ILINE1(3),ILINE2(3)
      COMPLEX STYP3(50,3,3)
      REAL*8 NAME(1)
      DO 100 I=1,3
      DELV1(I)=VVV(I,R)-VVV(I,S)
  100 DELV2(I)=VVV(I,P)-VVV(I,Q)
      CALL MULT(3,3,1,3,3,1,YRS,DELV1,OUT1)
      CALL MULT(3,3,1,3,3,1,YM1,DELV2,OUT2)
      DO 110 I=1,3
  110 ILINE1(I)=OUT1(I)+OUT2(I)
      INDEX1=INDEX+1
      DO 120 I=1,3
      DO 120 J=1,3
      YC1(I,J)=STYP3(INDEX,I,J)*ILEN
      YC2(I,J)=STYP3(INDEX1,I,J)*ILEN
      V1(I)=VVV(I,R)
  120 V2(I)=VVV(I,P)
      CALL MULT(3,3,1,3,3,1,YC1,V1,OUT1)
      CALL MULT(3,3,1,3,3,1,YC2,V2,OUT2)
      DO 121 I=1,3
      ILINE1(I)=ILINE1(I)+OUT1(I)
  121 ILINE2(I)=OUT2(I)
      CALL MULT(3,3,1,3,3,1,YM2,DELV1,OUT1)
      CALL MULT(3,3,1,3,3,1,YPQ,DELV2,OUT2)
      DO 122 I=1,3
  122 ILINE2(I)=ILINE2(I)+OUT1(I)+OUT2(I)
      CKT=1
      WRITE(6,7000)R,S,NAME(R),NAME(S),CKT
```

```
 7000 FORMAT('-',1X,I2,'-',I2,2X,'(',A6,'- ',A6,')',5X,'CKT. NO.',I2)
      CALL POWERO(R,S,M2,ILINE1,V1,VVVT,NAME)
      CKT=2
      WRITE(6,7000)P,Q,NAME(P),NAME(Q),CKT
      CALL POWERO(P,Q,M2,ILINE2,V2,VVVT,NAME)
      RETURN
      END
C
C
C
C     FAST KRON REDUCTION
C
      SUBROUTINE KRON3(IDIM,NB,K,ITEST,Y)
      INTEGER END
      COMPLEX Y(IDIM,IDIM),YNEW
      END=K-1
      ITEST=0
      DO 200 I=1,END
      IF(CABS(Y(I,K)).EQ.0.)GO TO 200
      IF(CABS(Y(K,K)).NE.0.)GO TO 400
      WRITE(6,1000)K
 1000 FORMAT('-',5X,'******* Y(K,K) IS 0.+J0. FOR K=',I3,'********')
      ITEST=1
      GO TO 210
  400 CONTINUE
      YNEW=Y(I,K)/Y(K,K)
      DO 100 J=I,END
      Y(I,J)=Y(I,J)-YNEW*Y(K,J)
      Y(J,I)=Y(I,J)
  100 CONTINUE
  200 CONTINUE
  210 CONTINUE
      RETURN
      END
C
C
C
C     SUBROUTINE TO COMPUTE UNBAL CURRENT AT THE GEN. SITE
C
      SUBROUTINE GENI(GVOLT,HVOLT,YT1,YTM2,IGEN,MAG,ANG)
      REAL MAG(3),ANG(3)
      COMPLEX GVOLT(3),HVOLT(3),YT1,YTM2,IGEN(3),DELV(3)
      DO 100 I=1,3
  100 DELV(I)=GVOLT(I)-HVOLT(I)
      IGEN(1)=(0.,0.)
      IGEN(2)=DELV(2)*YT1
      IGEN(3)=DELV(3)*YTM2
      CALL POLAR(3,IGEN,MAG,ANG)
      RETURN
      END
```

B. Sample Input Data Formats

The tables listed in this section represent sample data formats to aid the user in preparing data for the system reduction method program. Data should be entered with the specified formats in the same order that they are listed.

TABLE 32. Title card

			FORTRAN STATEMENT	IDENTIFICATION SEQUENCE
			TITLE CARD (write TITLE in 80 columns or less)	
			(A80)	
			Note: There should not be any blank lines in the following FORMATS.	
			All Z's are expressed in pu Ω/mi, except machines' and transformers' Z's.	
			All Y's are expressed in pu Mhos/mi.	
			All voltages are expressed in pu.	
			All powers are expressed in MVA (P in MW, Q in MVAR).	

TABLE 33. System MVA base and print-out option

STATEMENT NUMBER	FORTRAN STATEMENT	
BMVA		INFO
(F10.2)		(I5)

BMVA: System Base MVA

INFO: Printout option

0 Unbalances at the generator high voltage lines.

1 Line flow options in addition to 0 option.

TABLE 34. Outside of study area information

Outside of study area information

NT	NE	NOC	NM	IGN	OUTTP
(I5)	(I5)	(I5)	(I5)	(I5)	(I5)

NT:	Total number of buses in system (including the number of generator internal nodes).
NE:	Total number of elements outside the study area (including lines Z, $\frac{1}{2}Y_c$'s, shunts, loads, transformers, etc).
NOC:	Total number of couplines in the system outside the study area.
NM:	Number of mutually coupled elements = 2 x NOC.
IGN:	Total number of generators in the system.
OUTTP:	Number of element types entered.

TABLE 35. Study area information

Statement number	Study area information (FORTRAN STATEMENT)					
NE3	NOC3	INTP	ESN	ISN	SIGN	
(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	
NLINE	NLCHS	NLCHM				
(I5)	(I5)	(I5)				

NE3: Total number of elements inside of study area (lines [Z's], ½[Y_c], mutual [Z's], ½[Y_c], transformers, loads, etc).

NOC3: Number of couplings inside of study area.

INTP: Number of element types entered.

ESN: Number of nodes at the edge of study area.

ISN: Number of nodes inside the study area.

SIGN: Number of generators inside of study area.

NLINE: Number of series self [Z] for each configuration (e.g., n different configuration yield n [Z]'s).

NICHS: Number of self line chargings for each configuration.

NLCHM: Number of line chargings of mutual coupled lines.

TABLE 36. Outside of study area elements

Type and value of elements outside of study area — FORTRAN STATEMENT — IDENTIFICATION SEQUENCE

C	STATEMENT NUMBER									
	ITYPE									
	(I5)									
		R_0		X_0		R_1		X_1		R_2 X_2
		(E10.3)		(E10.3)		(E10.3)		(E10.3)		(E10.3) (E10.3)
9	9999									
	ITYPE		PP		QQ		VOLT			
	(I5)		(F10.5)		(F10.5)		(F10.5)			
9	9999								ITYPE:	Type number of uncoupled elements in increasing order.
									$R_{0,1,2}X_{0,1,2}$:	Uncoupled impedances.
	HTYPE								PP:	Three-phase power at the load, MW.
	(I5)								VOLT:	Magnitude of voltage at the load, PU.
		R_{H0}		X_{H0}					HTYPE:	Type number of coupled elements.
		(F10.6)		(F10.6)					R_{H0}, X_{H0}:	Zero sequence mutual impedance.
9	9999									

TABLE 37. Inside of study area uncoupled elements

Inside of study area impedance matrices or shunts — FORTRAN STATEMENT — IDENTIFICATION SEQUENCE

STATEMENT NUMBER						
ITYPE (I5)						
	R_{00} or G_{00}	X_{00} or G_{00}	R_{01} or G_{01}	X_{01} or B_{01}	R_{02} or G_{02}	X_{02} or B_{02}
	R_{10} or G_{10}	X_{10} or B_{10}	R_{11} or G_{11}	X_{11} or B_{11}	R_{12} or G_{12}	X_{12} or B_{12}
	R_{20} or G_{20}	X_{20} or B_{20}	R_{21} or G_{21}	X_{21} or B_{21}	R_{22} or G_{22}	X_{22} or B_{22}
	(E10.3)	(E10.3)	(E10.3)	(E10.3)	(E10.3)	(E10.3)
9 9999						

Note: Series impedance matrix should be entered as [Z].
Shunt admittance matrix should be entered as [Y], ½[Y] for line chargings.

STATEMENT NUMBER							
ITYPE (I5)	P_a (F10.3)	Q_a (F10.3)	P_b (F10.3)	Q_b (F10.3)	P_c (F10.3)	Q_c (F10.3)	VOLT (F10.6)
9 9999							

Note: P_i, Q_i $i = a,b,c$
represents P and Q in each phase of load in MW and MVAR, respectively.
VOLT: Magnitude of voltage at load (obtained from 1-ϕ load flow).

TABLE 38. Inside of study area coupled elements

Inside of study area (continued): mutual coupling — FORTRAN STATEMENT

	C	Statement number							Identification sequence
		HTYPE							
		(I5)							
1			R_{H00}	X_{H00}	R_{H01}	X_{H01}	R_{H02}	X_{H02}	
2			R_{H00}'	X_{H00}'	R_{H01}'	X_{H01}'	R_{H02}'	X_{H02}'	
3			R_{H10}	X_{H10}	R_{H11}	X_{H11}	R_{H12}	X_{H12}	
4			R_{H10}'	X_{H10}'	R_{H11}'	X_{H11}'	R_{H12}'	X_{H12}'	
			.	.	.	.	.	.	
11			$R_{H2'0}$	$X_{H2'0}$	$R_{H2'1}$	$X_{H2'1}$	$R_{H2'2}$	$X_{H2'2}$	
12			$R_{H2'0'}$	$X_{H2'0'}$	$R_{H2'1'}$	$X_{H2'1'}$	$R_{H2'2'}$	$X_{H2'2'}$	
	9	9999							

TABLE 39. Outside of study area zero-sequence connections: mutually coupled elements

Outside of study area: Zero sequence connections
Mutually coupled elements: Maximum of two elements per coupling

ES1	P	Q	SI1	ES2	R	S	SI2	SM	ILEN
(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	(F10.2)

ES1:	P-Q element number.
P,Q,R,S:	Node numbers of mutually coupled elements (normally P-Q coincides with R-S).
ES2:	R-S element number.
SI1:	Type number of element ES1.
SI2:	Type number of element ES2.
SM:	Type number of mutual impedance.
ILEN:	Length of the coupled lines, miles.

TABLE 40. Outside of study area zero-sequence connections: uncoupled elements

Uncoupled elements — FORTRAN STATEMENT

ES	P	Q	SII	ILEN
(I5)	(I5)	(I5)	(I5)	(F10.2)

ES: P-Q element number. Do not start ES from 1. The starting number for uncoupled elements (ES's) is 1 plus the total number of mutuals.

P,Q: Node numbers.

SII: Type number of element ES.

ILEN: Length of element ES, miles.

TABLE 41. Outside of study area positive-sequence and negative-sequence connections

Outside of study area: Positive and negative sequence connections.

P	M	ITYPE	ILEN
(I5)	(I5)	(I5)	(F10.2)
99999			

P,M: Node numbers.

ITYPE: Type number of element P-M.

ILEN: Length of line P-M, miles

TABLE 42. Inside of study area connections: coupled elements

Statement number	Inside of study area: Coupled elements						FORTRAN STATEMENT
NHE							
(I5)							
ES	R	S	EM	P	Q	MTYPE	ILEN
(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	(I5)	(F10.2)
99999							
NHE:	Number of mutually coupled elements. This number should be entered once followed by mutual elements information.						
R,S,P,Q:	Nodes of mutually coupled elements.						
ES,EM:	Element numbers of mutual elements.						
MTYPE:	Type of element.						
ILEN:	Length of mutual elements, miles.						
Note:	Begin numbering the mutual elements from 1.						

TABLE 43. Inside of study area connections: uncoupled elements

STATEMENT NUMBER	CONT.	FORTRAN STATEMENT: Uncoupled elements					IDENTIFICATION SEQUENCE
ES		P	Q	ITYPE	ILEN		
(I5)		(I5)	(I5)	(I5)	(F10.2)		
99999							
ES:		Element number. Begin ES from 1.					
P,Q:		Nodes of elements.					
ITYPE:		Type of element.					
ILEN:		Length of line, miles.					

TABLE 44. Voltages at the internal nodes of the generators

STATEMENT NUMBER	FORTRAN STATEMENT
	Voltages at the generators
VGG	
(F10.6)	
VGG:	Positive sequence voltage at the generators internal nodes.
Note:	One entry per line.

TABLE 45. Bus numbers and their names

STATEMENT NUMBER	FORTRAN STATEMENT
	Bus names inside of study area
I	Name
(I5)	A6
.	.
.	.
I:	Bus number.
NAME:	Bus name.

TABLE 46. Generator and its step-up power transformer reactances inside the study area

Inside of study area: Generator and its step-up transformer data

LVBUS	HVBUS	RT1	XT1	RTH2	XTH2
(I5)	(I5)	(F10.4)	(F10.4)	(F10.4)	(F10.4)

LVBUS: Node number of low voltage bus of transformer.

HVBUS: Node number of high voltage bus of transformer.

RT1,XT1: Positive sequence impedance of transformer.

RTH2,XTH2: Summation of negative sequence impedances of transformers and generators.

C. Sample Input Data

```
INSIDE: LINES UNBAL, LOADS BAL;-OUTSIDE: LINES & LOADS BAL
   100.00     1
   24    80     1     2     6    20
   31     1    12     7     1     2
    2     2     2
    1
 0.291E-03 0.147E-02 0.428E-04 0.495E-03 0.428E-04 0.495E-03
    2
 0.413E-03 0.176E-02 0.398E-04 0.640E-03 0.398E-04 0.640E-03
    3
 0.000E 00 0.200E-01 0.000E 00 0.100E 04 0.000E 00 0.100E 04
    4
 0.000E 00-0.404E 03 0.000E 00-0.231E 03 0.000E 00-0.231E 03
    5
 0.000E 00-0.422E 03 0.000E 00-0.295E 03 0.000E 00-0.295E 03
    6
 0.000E 00 0.100E 05 0.000E 00 0.100E 05 0.000E 00 0.100E 05
    7
 0.000E 00 0.100E 04 0.000E 00 0.200E-01 0.000E 00 0.411E-01
    8
 0.000E 00 0.000E 00 0.000E 00 0.000E 00 0.000E 00 0.000E 00
    9
 0.465E-04 0.239E-03 0.778E-05 0.900E-04 0.778E-05 0.900E-04
   10
 0.000E 00-0.204E 04 0.000E 00-0.127E 04 0.000E 00-0.127E 04 99999
   11   0.00000    90.0000    1.02570
   12   90.0000    30.0000    1.02479
   13   240.000    150.000    1.01824
   14   120.000    90.0000    1.00977
   15   180.000    150.000    1.03035
   16   90.0000    60.0000    1.03240
   17   150.000    120.000    1.02910
   18   0.00000    120.000    1.02760
   19   240.000    150.000    1.02639
   20   180.000    150.000    1.03260 99999
    1
 0.0000385 0.0001210 99999
    1
 0.291E-03 0.147E-02 0.156E-04-0.376E-04-0.496E-05-0.339E-04
-0.496E-05-0.339E-04 0.428E-04 0.495E-03-0.374E-04 0.201E-04
 0.156E-04-0.376E-04 0.387E-04 0.188E-04 0.428E-04 0.495E-03
    2
 0.413E-03 0.176E-02 0.182E-04-0.126E-04-0.201E-04-0.948E-05
-0.201E-04-0.948E-05 0.398E-04 0.640E-03-0.407E-04 0.237E-04
 0.182E-04-0.126E-04 0.409E-04 0.234E-04 0.398E-04 0.640E-03
```

```
     3
  0.000E 00 0.247E-02-0.184E-03-0.169E-04 0.184E-03-0.169E-04
  0.184E-03-0.169E-04 0.000E 00 0.433E-02 0.281E-03-0.163E-03
 -0.184E-03-0.169E-04-0.281E-03-0.163E-03 0.000E 00 0.433E-02
     4
  0.000E 00 0.237E-02-0.637E-04 0.368E-04 0.637E-04 0.368E-04
  0.637E-04 0.368E-04 0.000E 00 0.339E-02 0.189E-03-0.109E-03 -0.637E-04
 0.368E-04-0.189E-03-0.109E-03 0.000E 00 0.339E-02
     5
  0.000E 00 0.980E-03-0.641E-04 0.807E-05 0.641E-04 0.807E-05
  0.641E-04 0.807E-05 0.000E 00 0.158E-02 0.986E-04-0.547E-04 -0.641E-04
 0.807E-05-0.986E-04-0.547E-04 0.000E 00 0.158E-02
     6
  0.000E 00 0.980E-03-0.390E-04 0.514E-04 0.390E-04 0.514E-04
  0.390E-04 0.514E-04 0.000E 00 0.158E-02 0.967E-04-0.581E-04 -0.390E-04
 0.514E-04-0.967E-04-0.581E-04 0.000E 00 0.158E-02 99999
     7     90.00      80.00   90.0000     80.000      90.00      80.00
 1.026390 99999
     1
  0.930E-04 0.478E-03 0.448E-05-0.158E-04-0.116E-05-0.146E-04
  0.774E-04 0.242E-03 0.473E-05 0.104E-04-0.719E-05 0.828E-05
 -0.116E-05-0.146E-04 0.156E-04 0.180E-03-0.135E-04 0.722E-05
  0.661E-05-0.928E-05-0.260E-07-0.726E-05 0.691E-05-0.429E-05
  0.448E-05-0.158E-04 0.140E-04 0.678E-05 0.156E-04 0.180E-03
  0.358E-05-0.104E-04-0.717E-05 0.384E-05 0.473E-06-0.741E-05
  0.774E-04 0.242E-03-0.358E-05-0.104E-04 0.661E-05-0.928E-05
  0.930E-04 0.478E-03 0.133E-04 0.632E-05-0.160E-04 0.404E-05 -0.719E-05
 0.828E-05-0.473E-06-0.741E-05 0.691E-05-0.429E-05 -0.160E-04 0.404E-05
 0.156E-04 0.180E-03-0.129E-04 0.873E-05
  0.473E-05 0.104E-05-0.717E-05-0.384E-05-0.260E-07-0.726E-05
  0.133E-04 0.632E-05 0.130E-04 0.811E-05 0.156E-04 0.180E-03 99999
     1   21   24    9    2   21   24    9    1    330.00
     3   11   15    7      1.00
     4   12   16    7      1.00
     5   14   18    7      1.00
     6   13   17    7      1.00
     7    1   10    7      1.00
     8    5    9    7      1.00
     9    0   15    3      1.00
    10    0   16    3      1.00
    11    0   18    3      1.00
    12    0   17    3      1.00
    13    0    1    3      1.00
    14    0    5    3      1.00
    15   16   19    1    165.00
    16   18   19    1    165.00
    17   18   20    2     80.00
    18   17   20    1    165.00
    19   17   24    2     80.00
    20   15   21    1     33.00
```

21	15	23	1	33.00
22	22	23	2	80.00
23	16	22	1	165.00
24	3	19	1	33.00
25	4	18	1	33.00
26	5	20	2	80.00
27	5	24	1	165.00
28	6	21	2	80.00
29	7	15	2	80.00
30	2	22	2	80.00
31	1	23	1	165.00
32	0	20	6	1.00
33	0	16	4	165.00
34	0	19	4	165.00
35	0	18	4	165.00
36	0	19	4	165.00
37	0	18	5	80.00
38	0	20	5	80.00
39	0	17	4	165.00
40	0	20	4	165.00
41	0	17	5	80.00
42	0	24	5	80.00
43	0	24	10	330.00
44	0	21	10	330.00
45	0	15	4	33.00
46	0	21	4	33.00
47	0	15	4	33.00
48	0	23	4	33.00
49	0	22	5	80.00
50	0	23	5	80.00
51	0	16	4	165.00
52	0	22	4	165.00
53	0	3	4	33.00
54	0	19	4	33.00
55	0	4	4	33.00
56	0	18	4	33.00
57	0	5	5	80.00
58	0	20	5	80.00
59	0	5	4	165.00
60	0	24	4	165.00
61	0	6	5	80.00
62	0	21	5	80.00
63	0	7	5	80.00
64	0	15	5	80.00
65	0	2	5	80.00
66	0	22	5	80.00
67	0	1	4	165.00
68	0	23	4	165.00
69	0	24	10	330.00
70	0	21	10	330.00

71	0	18	11	1.00
72	0	21	12	1.00
73	0	7	13	1.00
74	0	23	14	1.00
75	0	19	15	1.00
76	0	4	16	1.00
77	0	2	17	1.00
78	0	22	18	1.00
79	0	6	19	1.00
80	0	3	20	1.00
11	15	8	1.00	
12	16	7	1.00	
14	18	7	1.00	
13	17	7	1.00	
1	10	7	1.00	
5	9	7	1.00	
0	15	3	1.00	
0	16	3	1.00	
0	18	3	1.00	
0	17	3	1.00	
0	1	3	1.00	
0	5	3	1.00	
21	24	9	330.00	
21	24	9	330.00	
16	19	1	165.00	
18	19	1	165.00	
18	20	2	80.00	
17	20	1	165.00	
17	24	2	80.00	
15	21	1	33.00	
15	23	1	33.00	
22	23	2	80.00	
16	22	1	165.00	
3	19	1	33.00	
4	18	1	33.00	
5	20	2	80.00	
5	24	1	165.00	
6	21	2	80.00	
7	15	2	80.00	
2	22	2	80.00	
1	23	1	165.00	
0	20	6	1.00	
0	16	4	165.00	
0	19	4	165.00	
0	18	4	165.00	
0	19	4	165.00	
0	18	5	80.00	
0	20	5	80.00	
0	17	4	165.00	
0	20	4	165.00	

0	17	5	80.00	
0	24	5	80.00	
0	24	10	330.00	
0	21	10	330.00	
0	15	4	33.00	
0	21	4	33.00	
0	15	4	33.00	
0	23	4	33.00	
0	22	5	80.00	
0	23	5	80.00	
0	16	4	165.00	
0	22	4	165.00	
0	3	4	33.00	
0	19	4	33.00	
0	4	4	33.00	
0	18	4	33.00	
0	5	5	80.00	
0	20	5	80.00	
0	5	4	165.00	
0	24	4	165.00	
0	6	5	80.00	
0	21	5	80.00	
0	7	5	80.00	
0	15	5	80.00	
0	2	5	80.00	
0	22	5	80.00	
0	1	4	165.00	
0	23	4	165.00	
0	24	10	330.00	
0	21	10	330.00	
0	18	11	1.00	
0	21	12	1.00	
0	7	13	1.00	
0	23	14	1.00	
0	19	15	1.00	
0	4	16	1.00	
0	2	17	1.00	
0	22	18	1.00	
0	6	19	1.00	
0	3	20	1.00	99999
11	15	7	1.00	
12	16	7	1.00	
14	18	7	1.00	
13	17	7	1.00	
1	10	7	1.00	
5	9	7	1.00	
0	15	3	1.00	
0	16	3	1.00	
0	18	3	1.00	
0	17	3	1.00	

0	1	3	1.00
0	5	3	1.00
21	24	9	330.00
21	24	9	330.00
16	19	1	165.00
18	19	1	165.00
18	20	2	80.00
17	20	1	165.00
17	24	2	80.00
15	21	1	33.00
15	23	1	33.00
22	23	2	80.00
16	22	1	165.00
3	19	1	33.00
4	18	1	33.00
5	20	2	80.00
5	24	1	165.00
6	21	2	80.00
7	15	2	80.00
2	22	2	80.00
1	23	1	165.00
0	20	6	1.00
0	16	4	165.00
0	19	4	165.00
0	18	4	165.00
0	19	4	165.00
0	18	5	80.00
0	20	5	80.00
0	17	4	165.00
0	20	4	165.00
0	17	5	80.00
0	24	5	80.00
0	24	10	330.00
0	21	10	330.00
0	15	4	33.00
0	21	4	33.00
0	15	4	33.00
0	23	4	33.00
0	22	5	80.00
0	23	5	80.00
0	16	4	165.00
0	22	4	165.00
0	3	4	33.00
0	19	4	33.00
0	4	4	33.00
0	18	4	33.00
0	5	5	80.00
0	20	5	80.00
0	5	4	165.00
0	24	4	165.00

```
0    6    5     80.00
0   21    5     80.00
0    7    5     80.00
0   15    5     80.00
0    2    5     80.00
0   22    5     80.00
0    1    4    165.00
0   23    4    165.00
0   24   10    330.00
0   21   10    330.00
0   18   11      1.00
0   21   12      1.00
0    7   13      1.00
0   23   14      1.00
0   19   15      1.00
0    4   16      1.00
0    2   17      1.00
0   22   18      1.00
0    6   19      1.00
0    3   20      1.00 99999
2
1    4    5    2    4    5    1     165.00 99999
1    1    2    1   165.00
2    2    3    1    33.00
3    3    4    2    80.00
4    3    8    1   330.00
5    1    7    1   165.00
6    6    7    2    80.00
7    6    8    1   330.00
8    7    8    1    33.00
9    0    8    7     1.00
10   0    1    3   165.00
11   0    2    3   165.00
12   0    2    3    33.00
13   0    3    3    33.00
14   0    3    4    80.00
15   0    4    4    80.00
16   0    3    3   330.00
17   0    8    3   330.00
18   0    6    3   330.00
19   0    8    3   330.00
20   0    6    4    80.00
21   0    7    4    80.00
22   0    1    3   165.00
23   0    7    3   165.00
24   0    4    5   165.00
25   0    5    5   165.00
26   0    4    6   165.00
27   0    5    6   165.00
28   0    7    3    33.00
```

```
 29    0    8    3      33.00 99999
.999655     .026247
.999062     -.0433
1.0         0.
.996891    -.078798
.984249     .176786
.999588    -.028701
  1HBUS3
  2LOAD11
  3LOAD10
  4LOAD9
  5LOAD8
  6LOAD12
  7LOAD14
  8LOAD13
  9REG18
 10REG16
  9    5   0.00000   0.02000   0.00000   0.04110
 10    1   0.00000   0.02000   0.00000   0.04110
```